



# **Novel Techniques for generation of ultra-spectrally pure signals, and ultra-high dynamic range true time delay for optical signal processing**

Lute Maleki

*Quantum Sciences and Technology Group*  
Jet Propulsion Laboratory

LM / AOSP 8/02

**APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED**



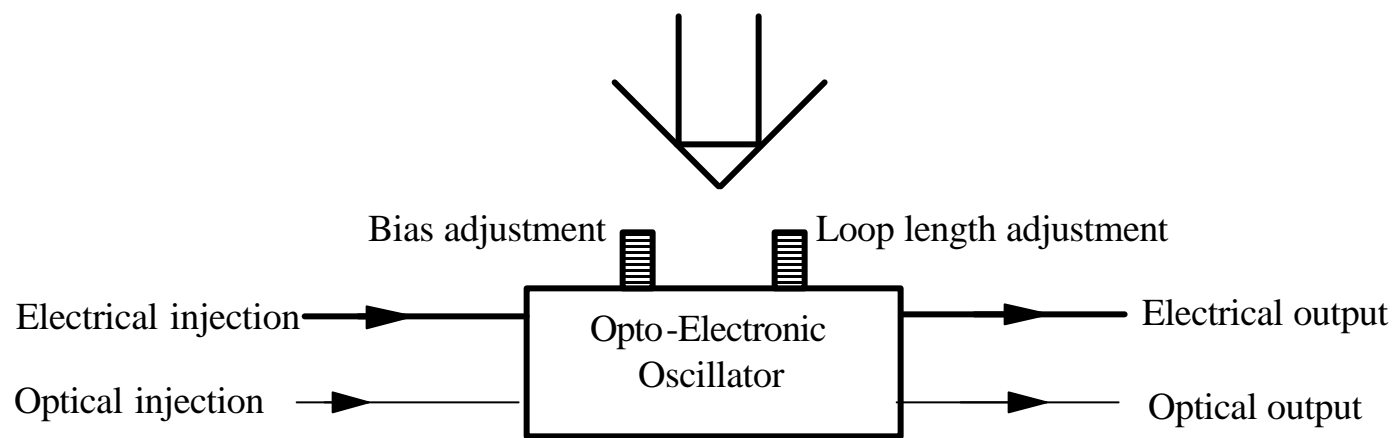
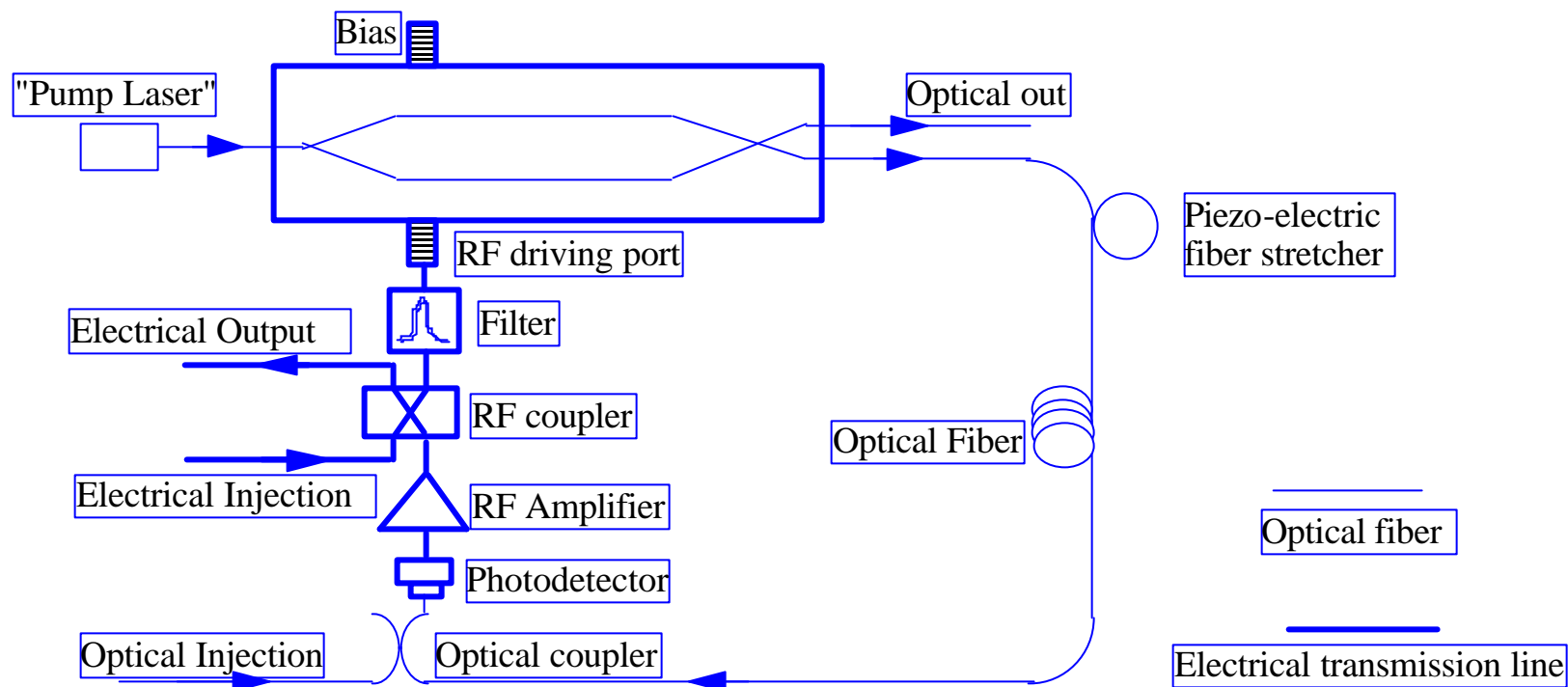
# Objective



- Develop an improved performance Opto-Electronic Oscillator (25 dB phase noise improvement across the Fourier spectrum)
- Develop a novel widely tunable true time delay device based on quantum coherence control



# OEO as a Generic Frequency Control Device



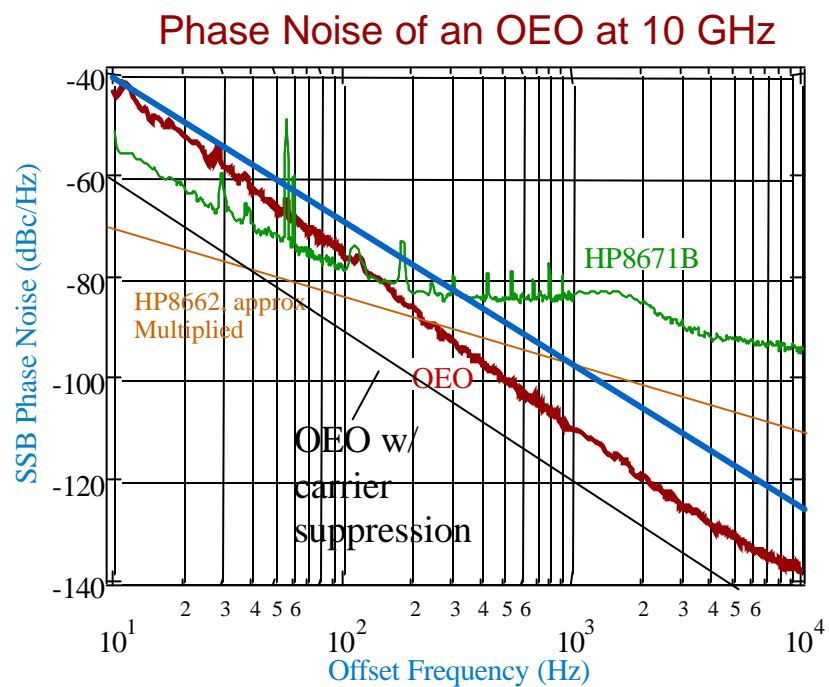
LM7/AOSP 8/02

## Some significant features

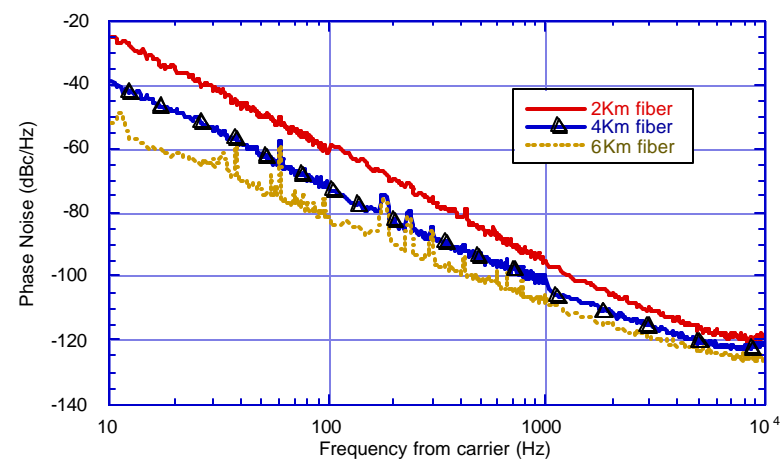
- OEO is a generic device: various configurations of lasers, modulators, optical delays can be implemented
- OEO lends itself to diverse **architecture** (dual loop, Coupled OEO, etc) to support diverse applications
- OEO's performance **will improve with improved components** (amplifiers, lasers, modulators, detectors, optical delays)
- OEO is ideal for **opto-electronic integration**
- The OEO **signal is available both electrically, and on an optical carrier**
- The COEO version generates short (sub-picosecond) mode locked **optical pulses with lowest jitter**
- OEO can be **phase locked, frequency locked, self locked, and used as a VCO**



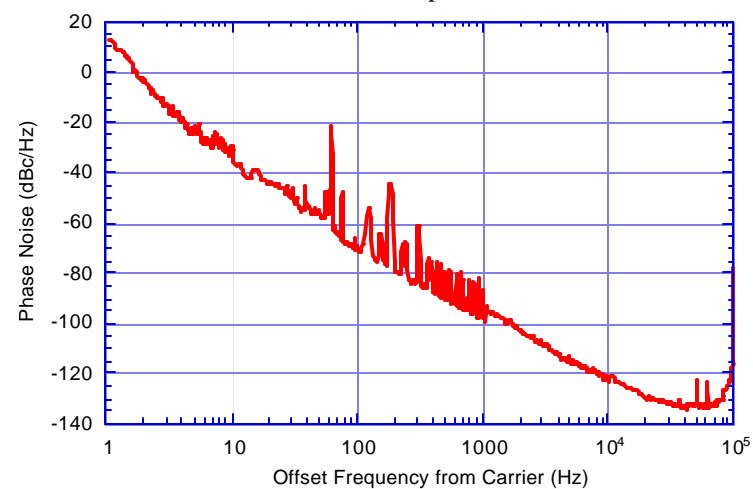
## 10 GHz OEO



Phase Noise of Compact OEO (12/14/98)



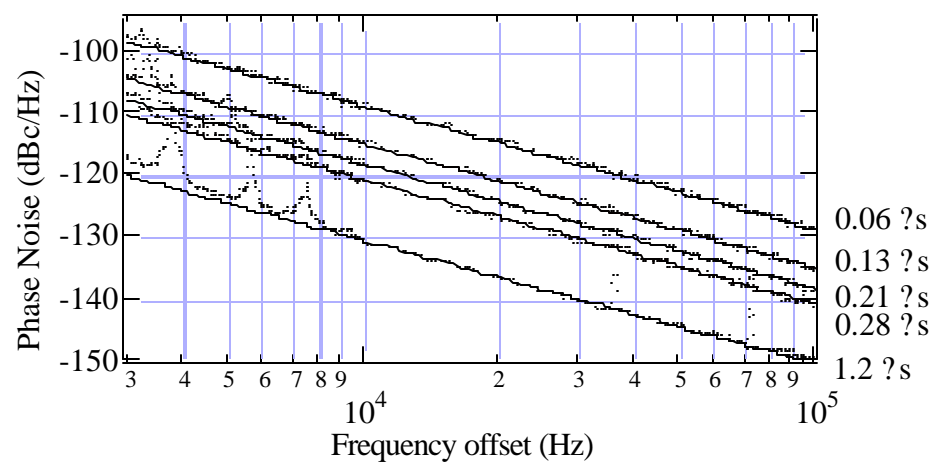
Phase Noise of Compact 30 GHz OEO



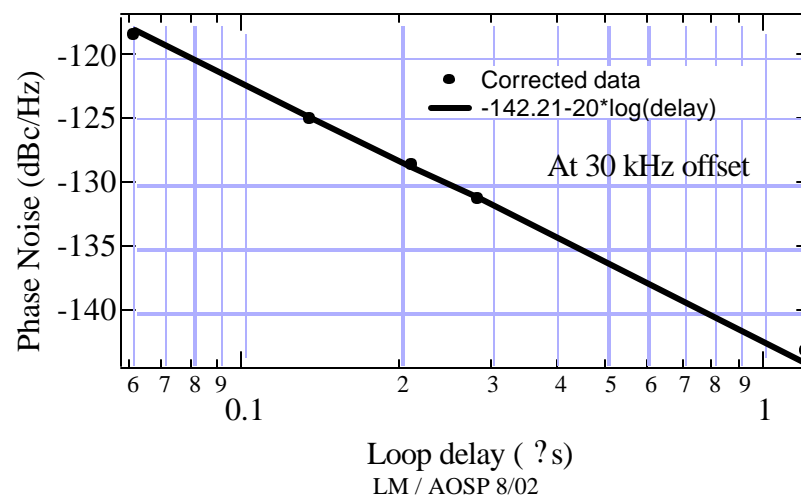
## Demonstrated features of OEO

- Highest demonstrated spectral purity for any open loop oscillator at 10 GHz (-145 dBc/Hz at 10 kHz from the carrier)
- Demonstration of up to 20 dB better performance than this, at frequencies close to carrier, with carrier suppression technique
- Demonstrated 30 GHz oscillator, with spectral purity of -120 dBc/Hz at 10 kHz from the carrier, limited only by the amplifier
- Demonstrated that low noise OEO is also inherently insensitive to acceleration: 10 GHz OEO exhibits the lowest acceleration sensitivity of any oscillator, with room to improve.
- Demonstrated that the OEO fiber spool may be replaced by a sub-millimeter microsphere, and designed a chip based OEO
- Demonstrated wideband and narrowband tuning with a 10 GHz OEO
- Demonstrated multi-tone and enhanced filtering with dual-loop

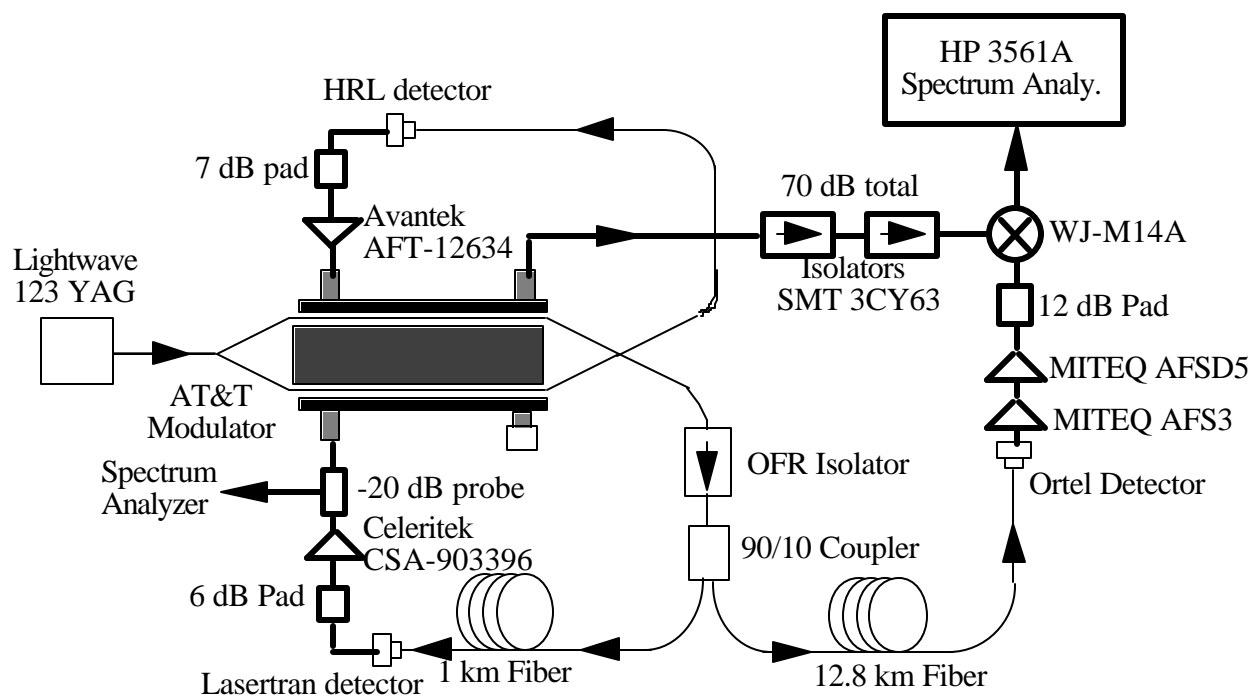
Phase noise vs. frequency offset



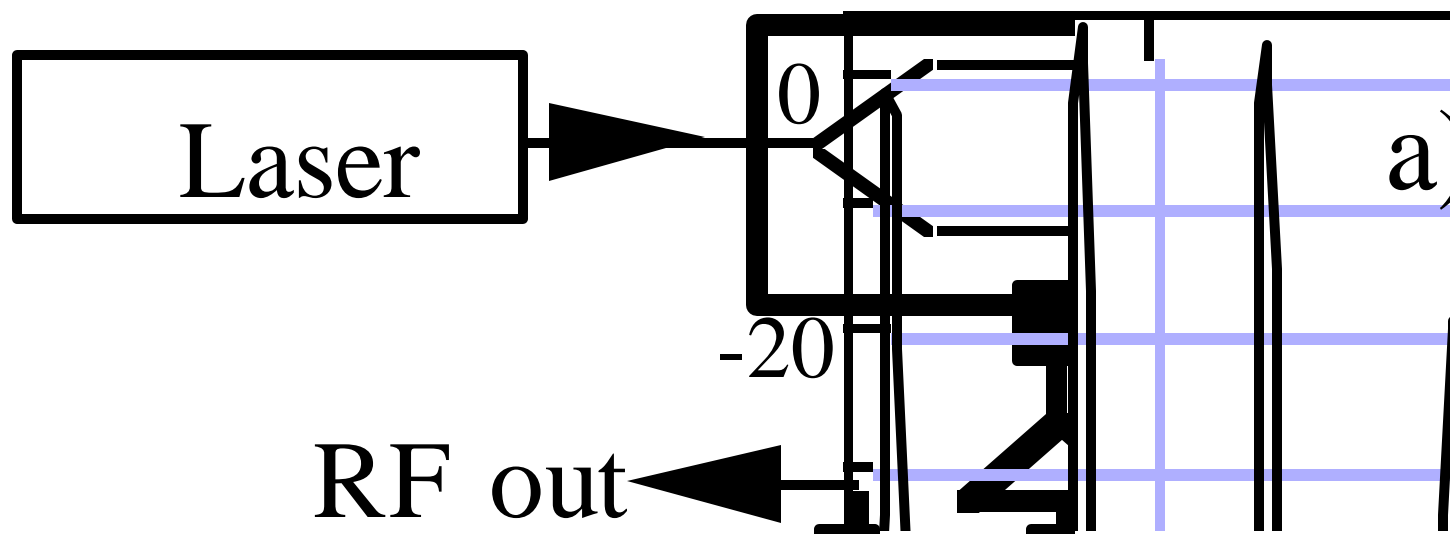
Phase noise vs. loop delay time



## Noise Measurement Set Up

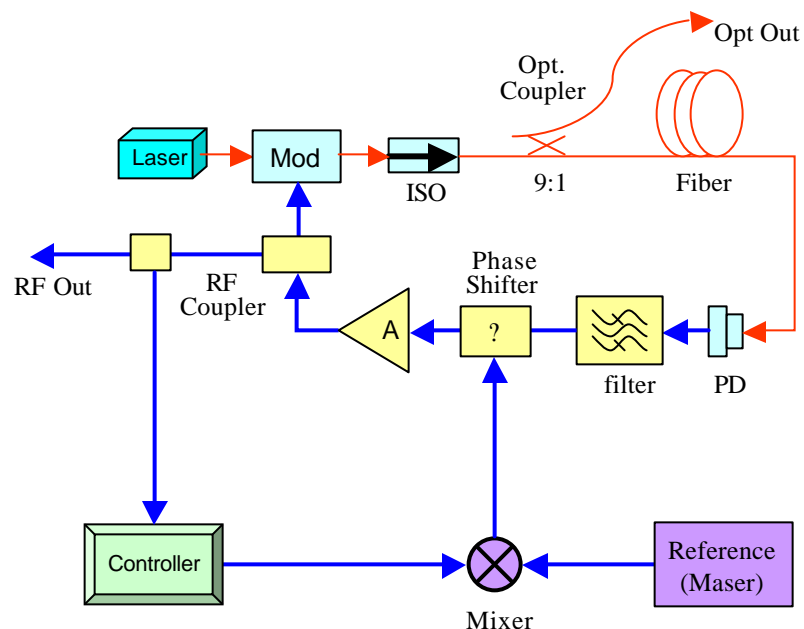


## The Dual-Loop OEO



Reduces side modes to lower than  $-100$  dBc

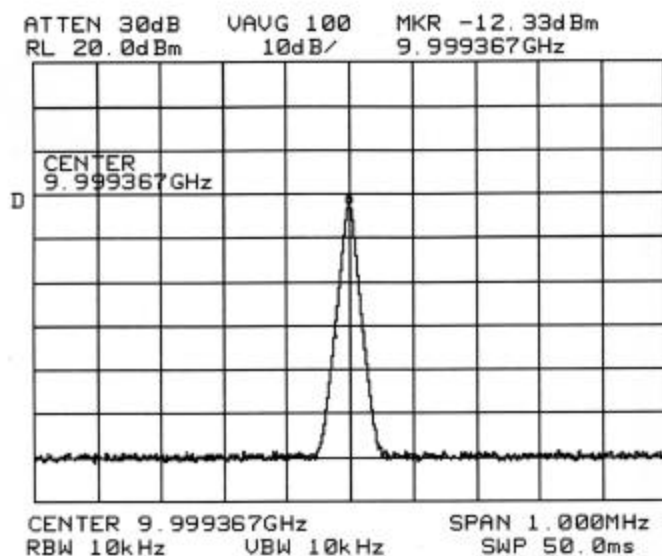
## Phase Locked OEO / Optical Synthesizer



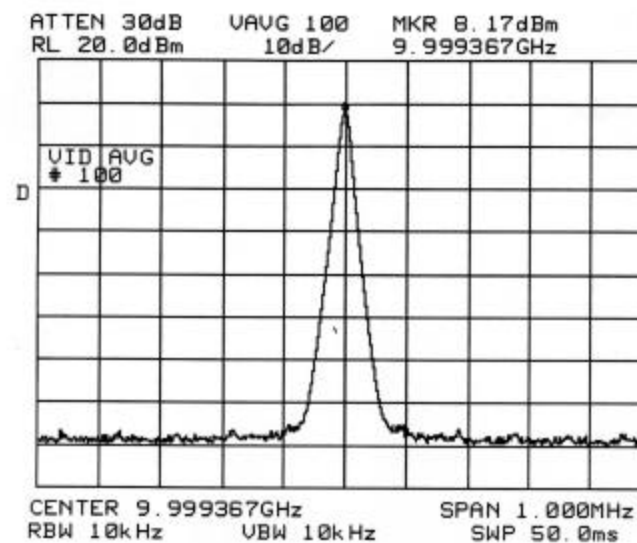
Phase locking of the OEO allows its use as a local oscillator to achieve long term stability. This capability is needed, for example, to enable *GPS style navigation at Mars*.



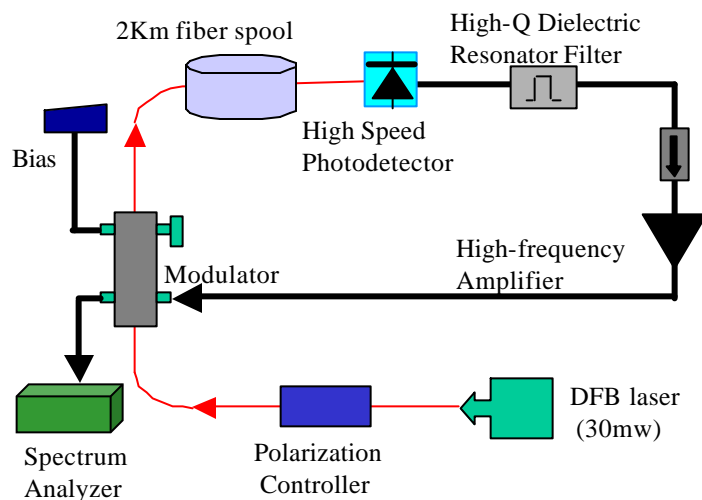
## Signal to Noise ratio of the injected and injection Locked signals



(a) Injected signal from HP synthesizer

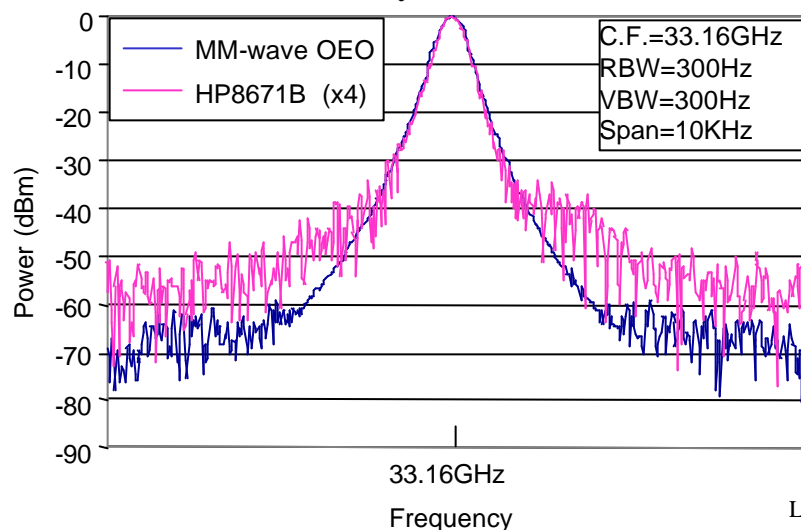


(b) Signal of injection locked OEO  
(nearest side modes at 90kHz  
suppressed by >15dB)

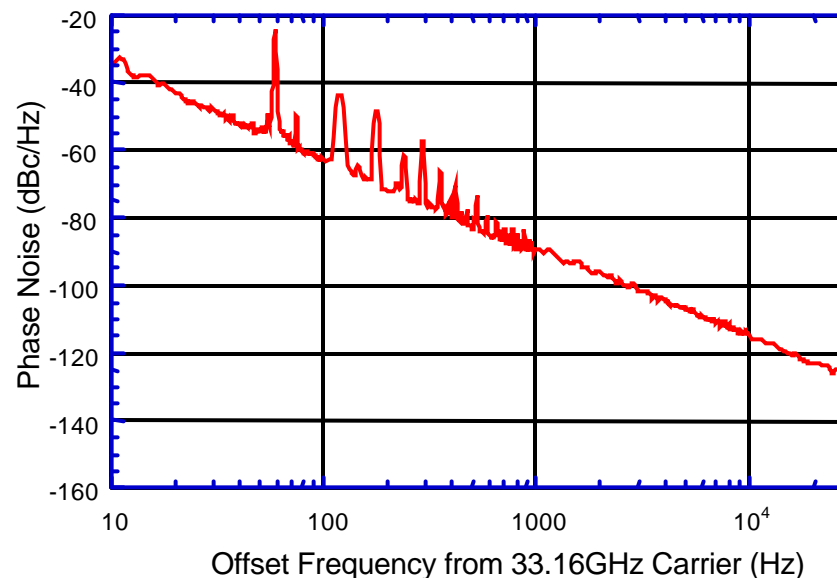


- Oscillating up to 33 GHz.
- Phase noise less than -30dBc/Hz at 10Hz and -120dBc/Hz at 10 KHz from both 28.29GHz and 33.16GHz carriers.
- Phase noise of mm-wave OEO is 20dB lower than that of the HP synthesizer with a 4<sup>th</sup> multiplier.

Comparison of Millimeter-wave OEO and HP Synthesizer



Phase Noise of 33.16GHz OEO

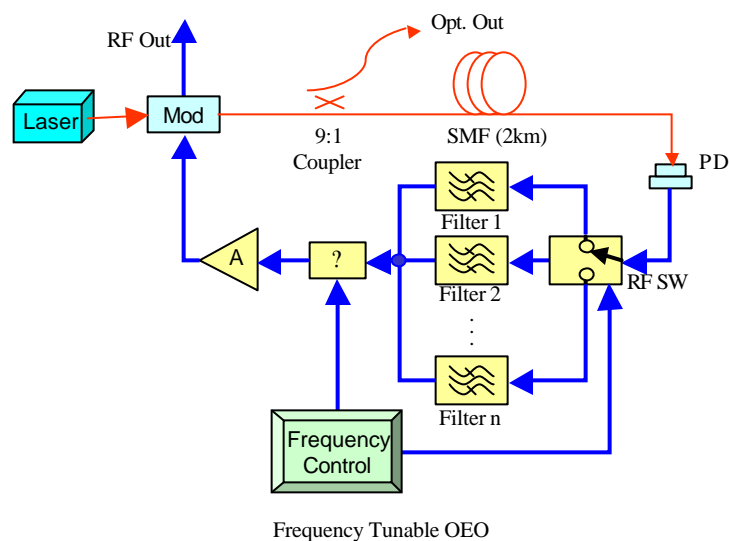




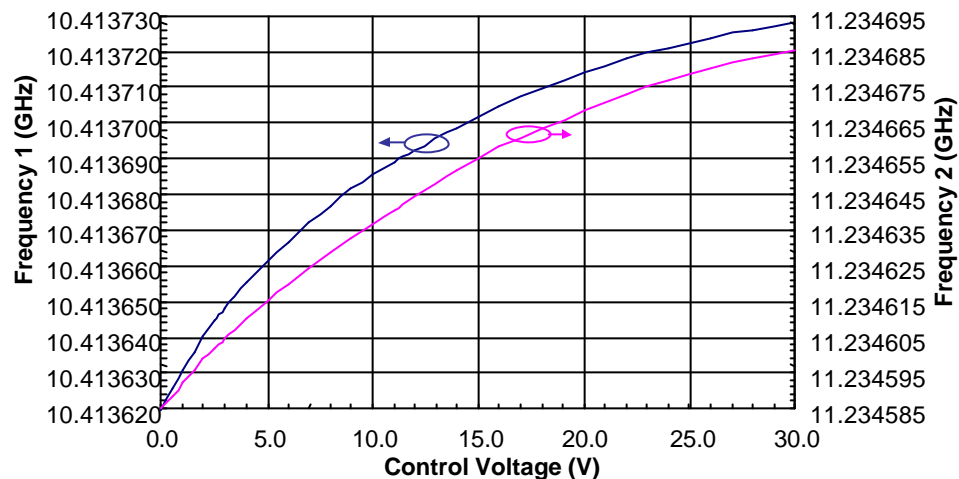
# Frequency Tunable OEO



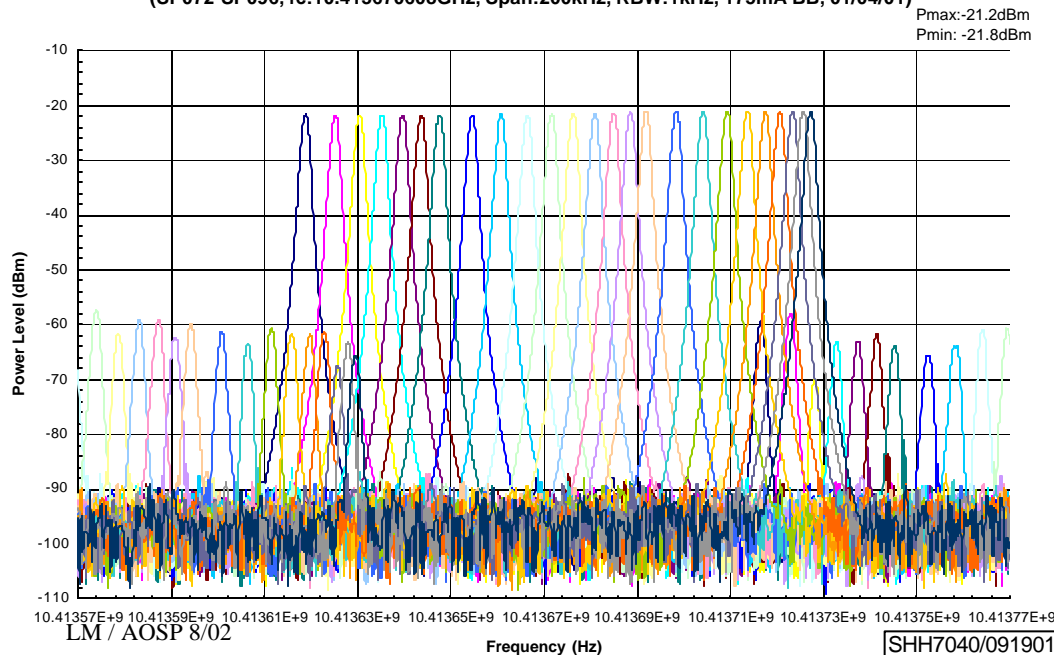
Frequency tunability will enhance the use of the OEO as a VCO for communications and radar applications



Tunable OEO Frequency vs. Control Voltage (01/04/01)



Spectrum of OEO5 (Tune frequency by changing control voltage)  
(SP072-SP096, fc:10.413670608GHz, Span:200kHz, RBW:1kHz, 175mA BB, 01/04/01)

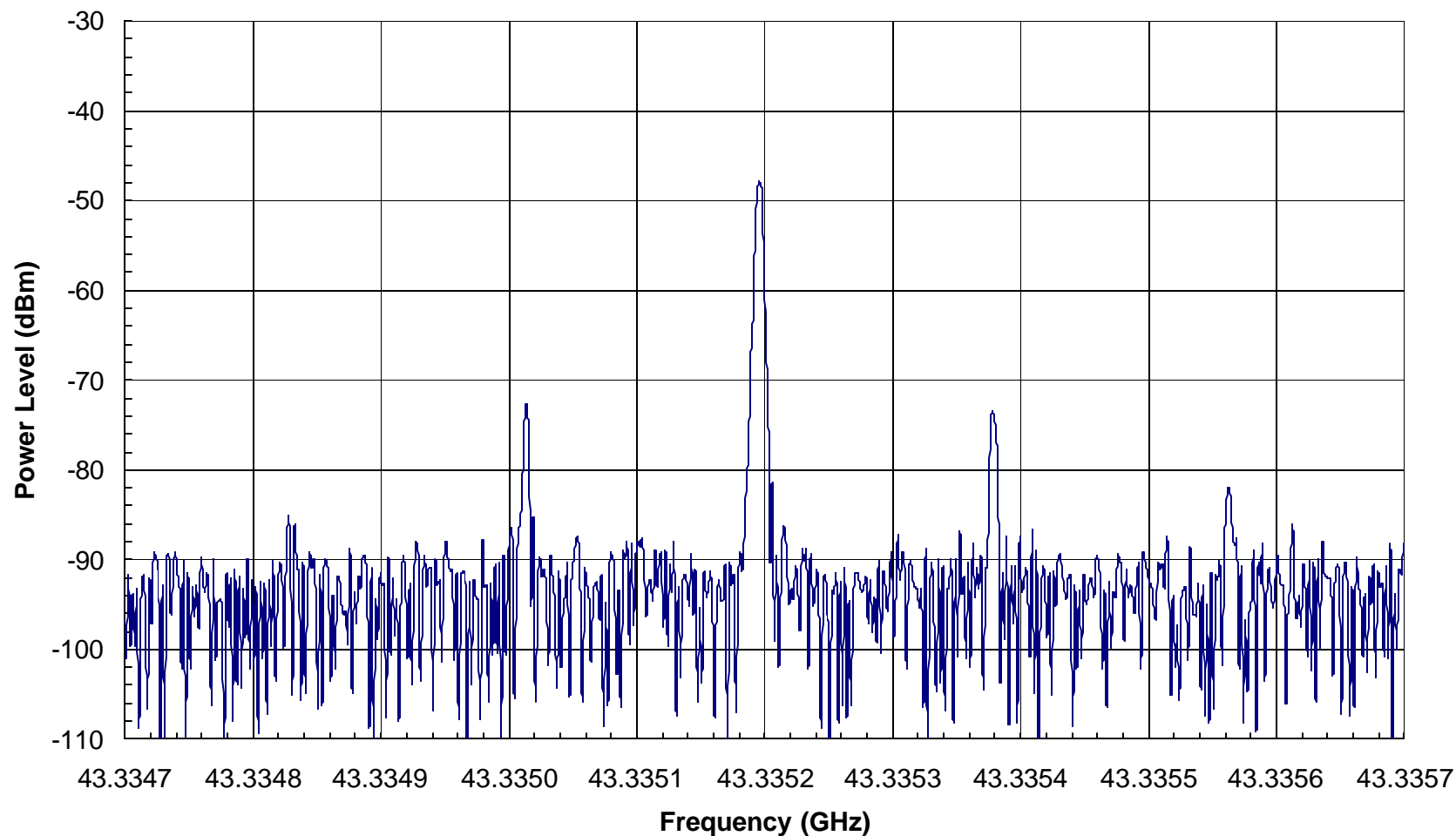




# Ka-Band / Millimeter-wave OEO



Spectrum of KaOEO03  
(SP109, 100N, fc:43.335243450GHz, Span:1MHz, RBW:3kHz, 09/10/01)



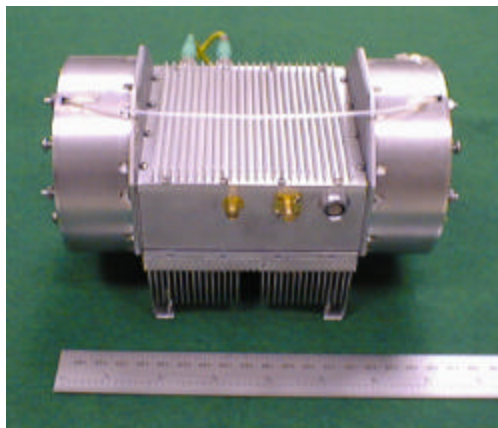
LM / AOSP 8/02

SHH7044/091901

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



# Packaged OEO with Vibration Compensation



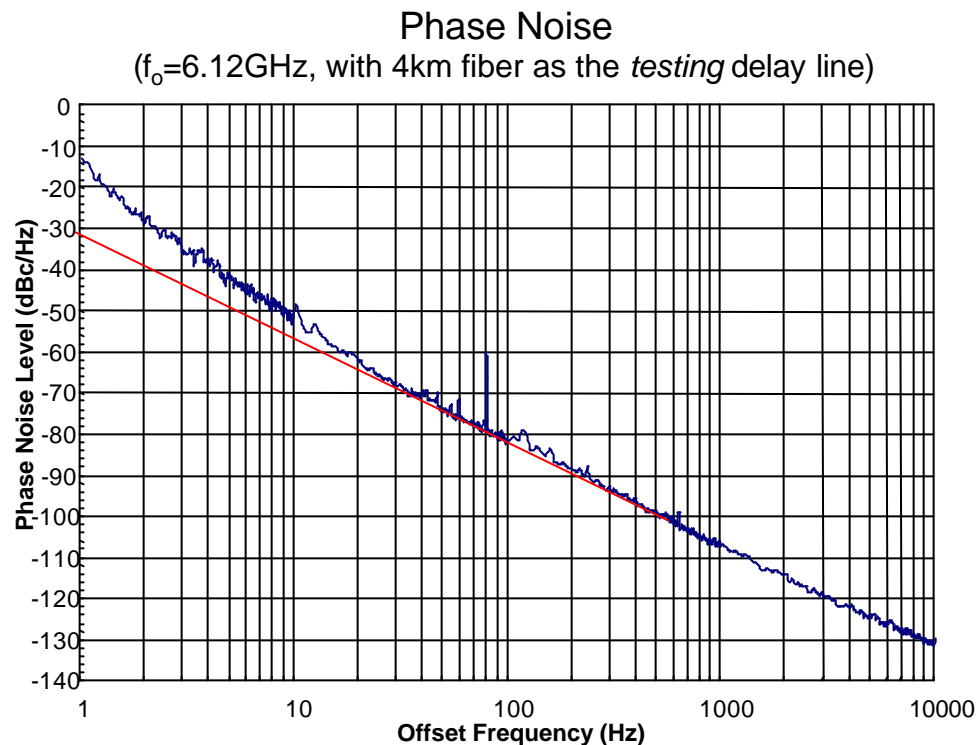
- Packaged OEO with vibration compensation (reduced the acceleration sensitivity).

Vibration Test Results (without fiber delay line compensation)  
OEO-2,  $f_c=11.763$  GHz,  $F_v=40$  Hz, Value in  $10^{-10}/G$

Number of Test	? x	? y	? z	??
1	0.713	0.650	32.259	32.273
2	0.465	0.900	32.146	32.162
3	0.453	1.124	30.870	30.894
4	0.584	0.982	31.484	31.505
5	0.556	0.485	33.886	33.894
Average	0.554	0.828	32.129	32.144

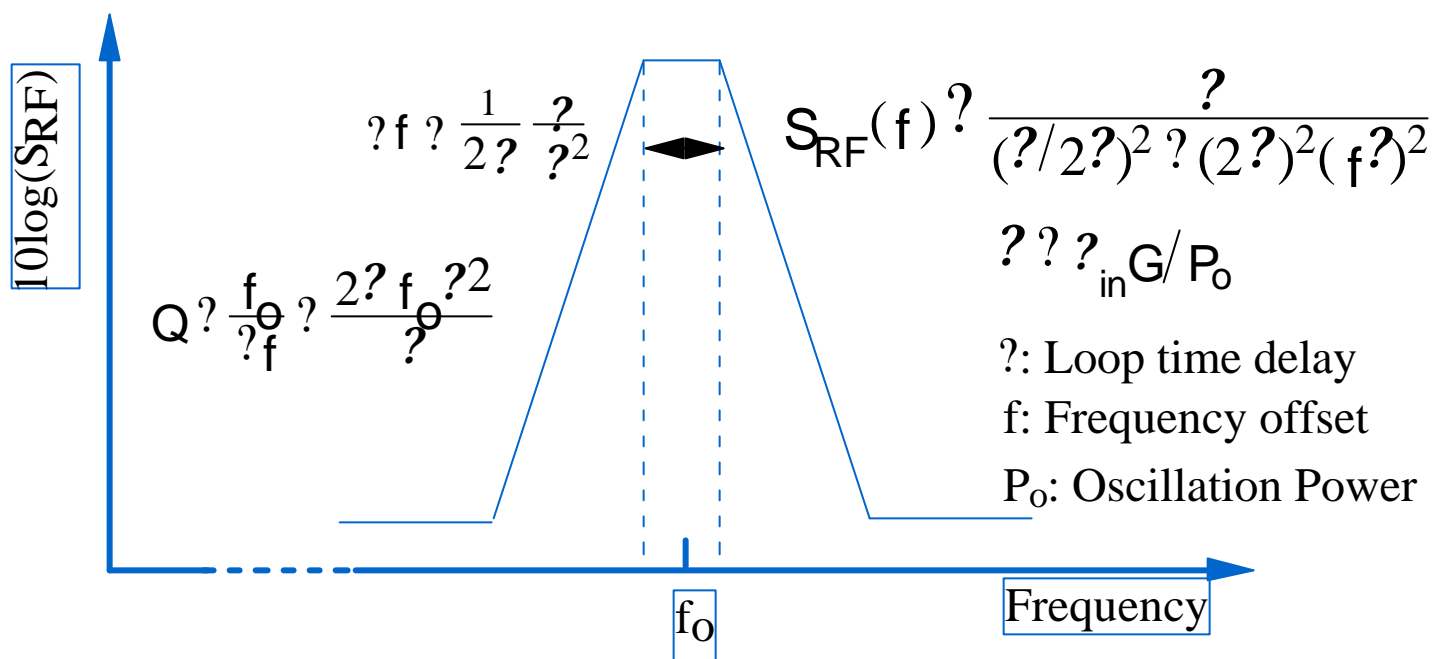
Vibration Test Results (with fiber delay line compensation)  
OEO-2,  $f_c=11.763$  GHz,  $F_v=40$  Hz, Value in  $10^{-10}/G$

Number of Test	? x	? y	? z	??
1	0.713	0.650	0.970	1.368
2	0.465	0.900	1.140	1.525
3	0.453	1.124	0.460	1.296
4	0.584	0.982	0.820	1.406
5	0.556	0.485	0.740	1.045
Average	0.554	0.828	0.826	1.294



# OEO Sources of Noise

- Analysis of the OEO noise sources



$P_{in} \Rightarrow$  Input noise power density

$G$  Thermal noise  $\tau$  Shot noise  $\tau$  Laser RIN noise

\* Noise decays with  $f$ : 20 dB/Decade

Typical  $\tau \sim 5 \times 10^{-17}/\text{Hz}$

\* Noise decays with  $\tau$ : 20 dB/decade

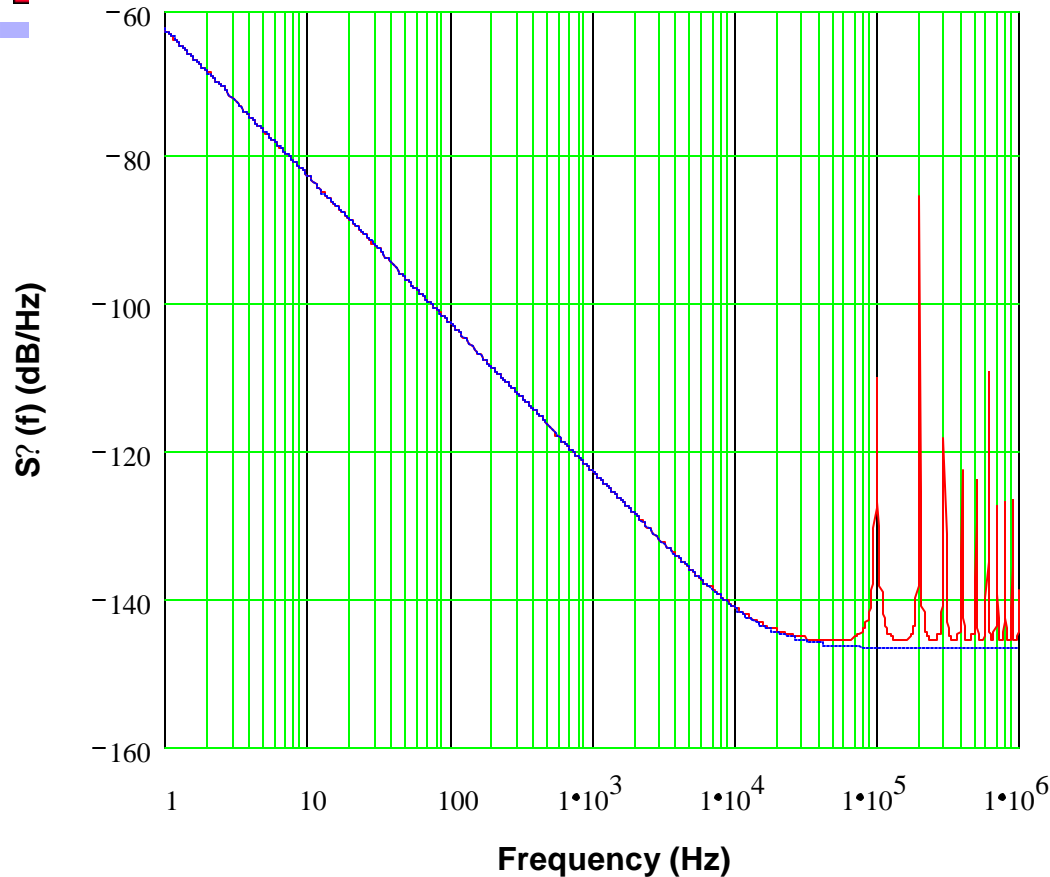
For  $\tau = 6 \text{ ns}$  (1 km fiber)

\* Noise is independent of oscillation frequency  $f_0$ .

$Q \sim 4 \times 10^{-5} f_0 \text{ (Hz)}$

\*  $Q$  increases with  $f_0$ .

Graph showing resonances in 2km fiber



Mathcad plot of 2 forms of  $S_{phi}$  at bottom of this page ( $S_{rf}$  and  $S_{rff}$ ). The first form is a low-frequency approximation plotted as the dashed line. Using white noise sources only here.

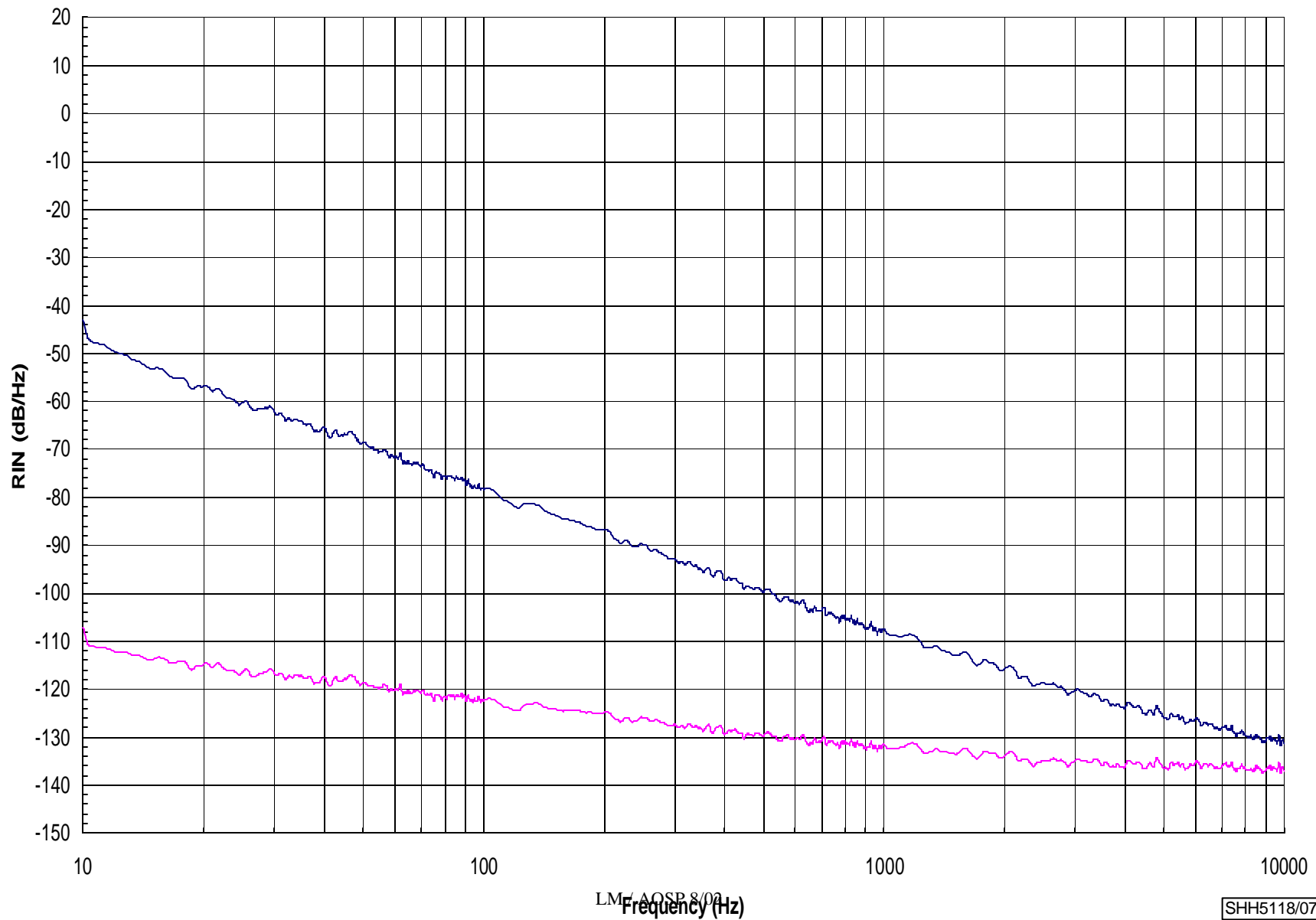
$$N := kb \cdot Tnf(NF \cdot T) + 2 \cdot e_{minus} \cdot I_{ph} \cdot R + N_{rin} \cdot I_{ph}^2 \cdot R \quad \gamma := \frac{N}{P_{osc}}$$

$$S_{rf}(f) := \gamma \cdot \left[ 1 + \frac{1}{(2 \cdot \gamma \cdot f)^2} \right] \quad S_{rff}(g) := \gamma \cdot \left[ 1 + \frac{1}{2 \cdot (1 - \cos(2 \cdot \gamma \cdot g))} \right]$$

LM / RSC 3/92



RIN of Semiconductor Laser  
(LN010, Alcatel A1915LMI, I:60mA, P:4.8mW, Pr:3mW, 07/15/02)



LM-AOSP 8/02

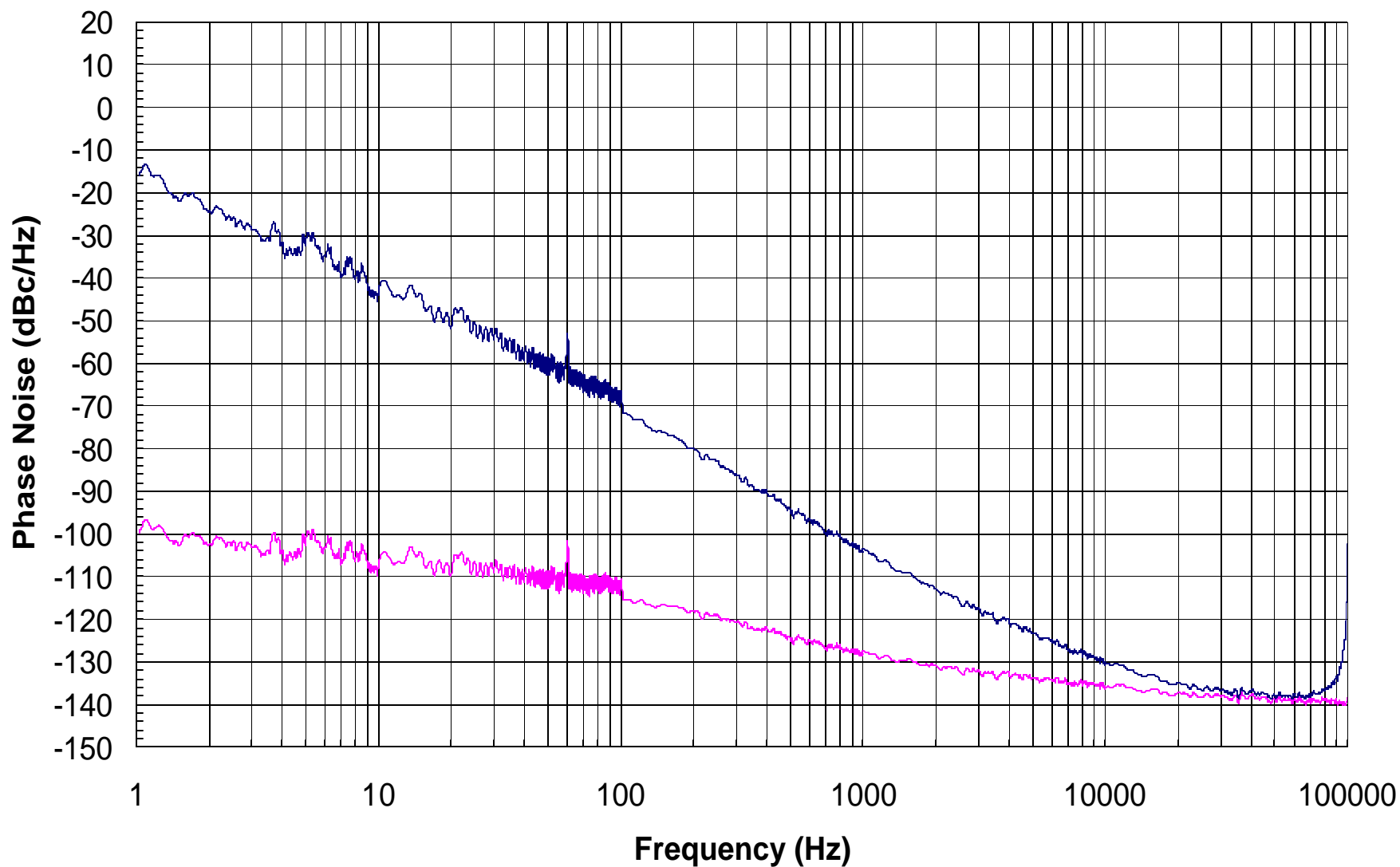
SHH5118/071602

APPROVED FOR PUBLIC RELEASE - DISTRIBUTION UNLIMITED



# Phase Noise of Amplifier

(PNAMP50, MSH-6642501-LP, S/N:104,  $f_c$ :10.58GHz, 11/17/00)



LM / AOSP 8/02

SHH5074/062101

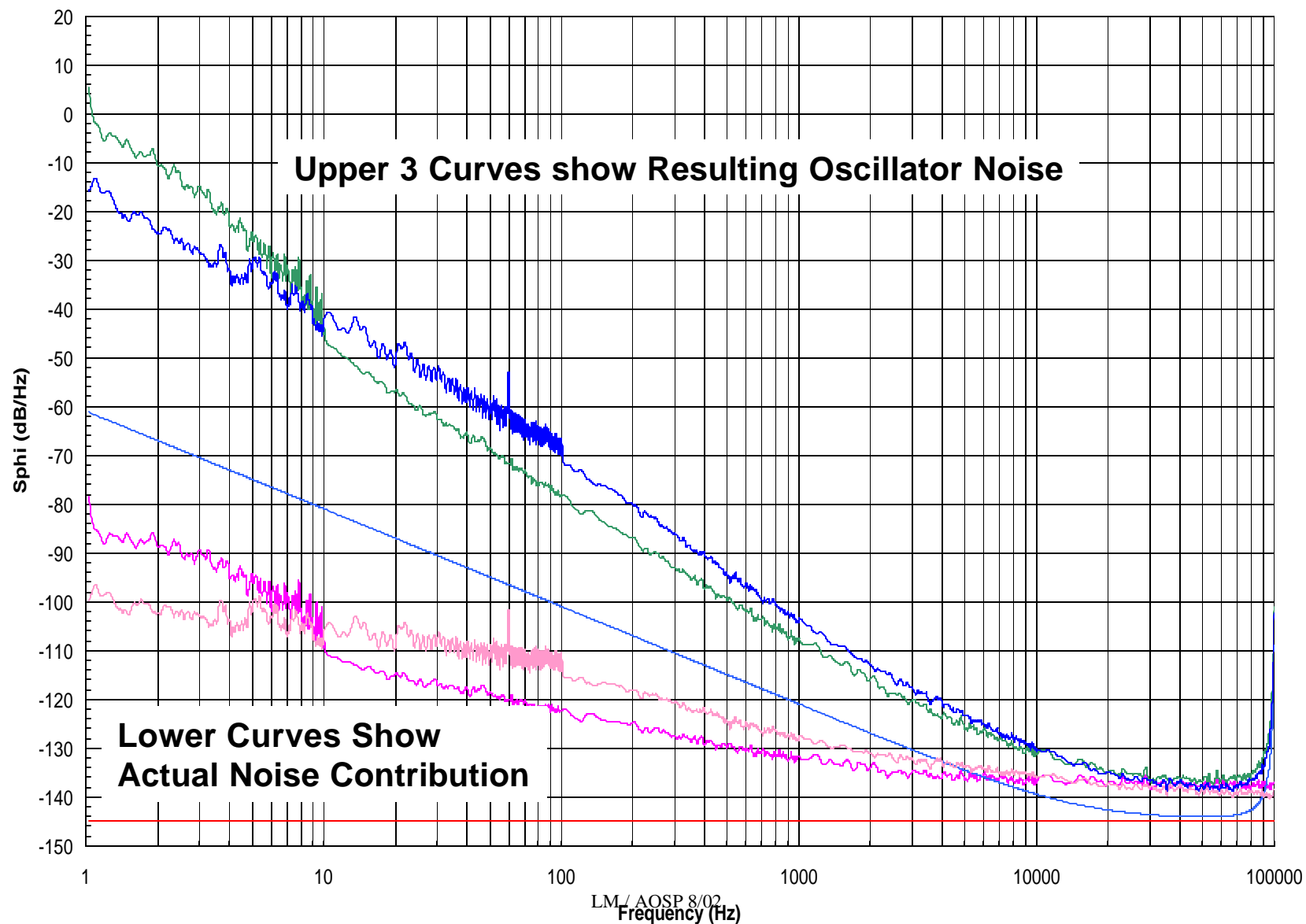
APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



# Shot Noise, RIN, and Amplifier Noise



## OEO with 2km Fiber Length



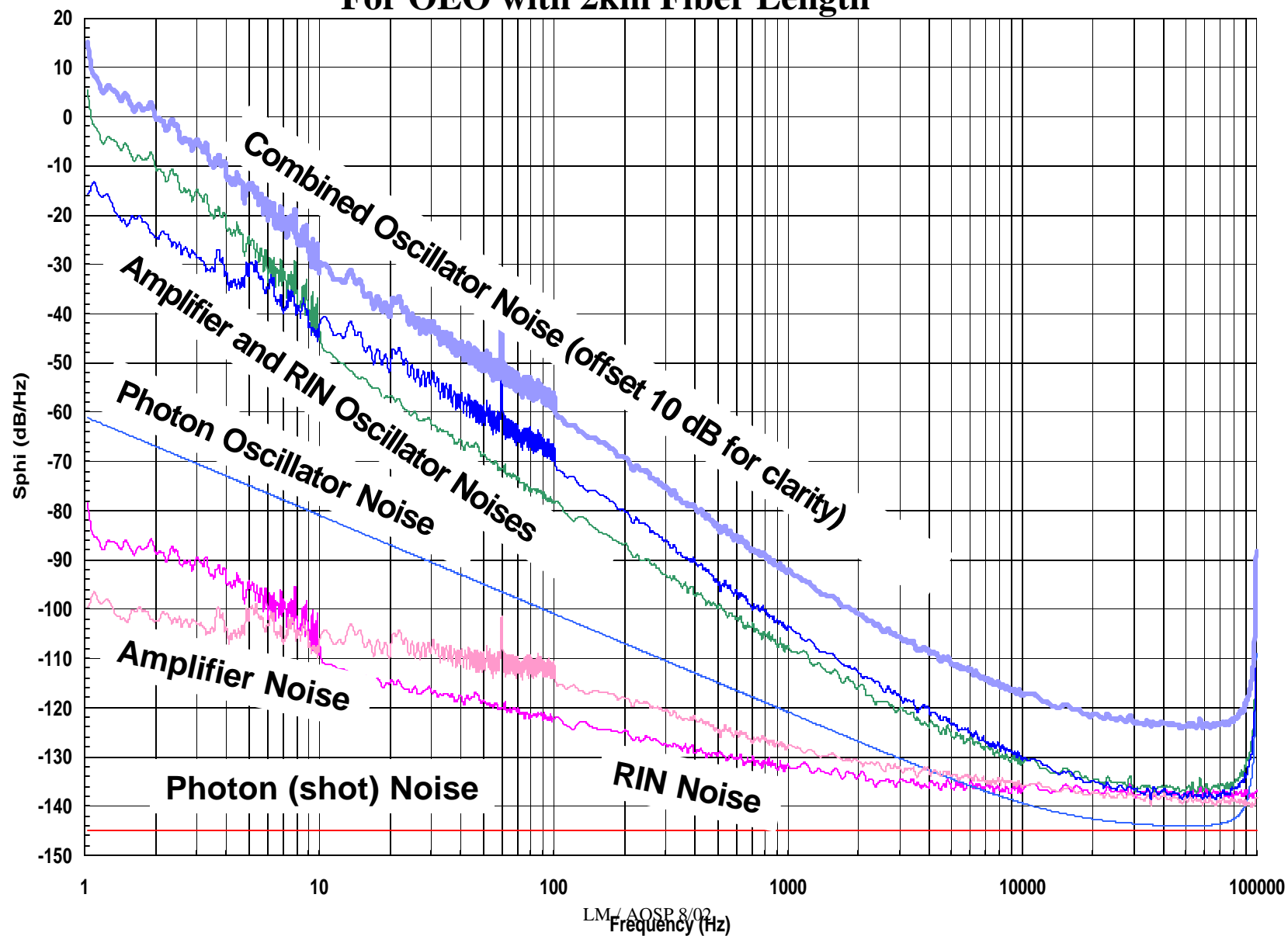
APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



# Noise Sources and Effect on Phase Noise



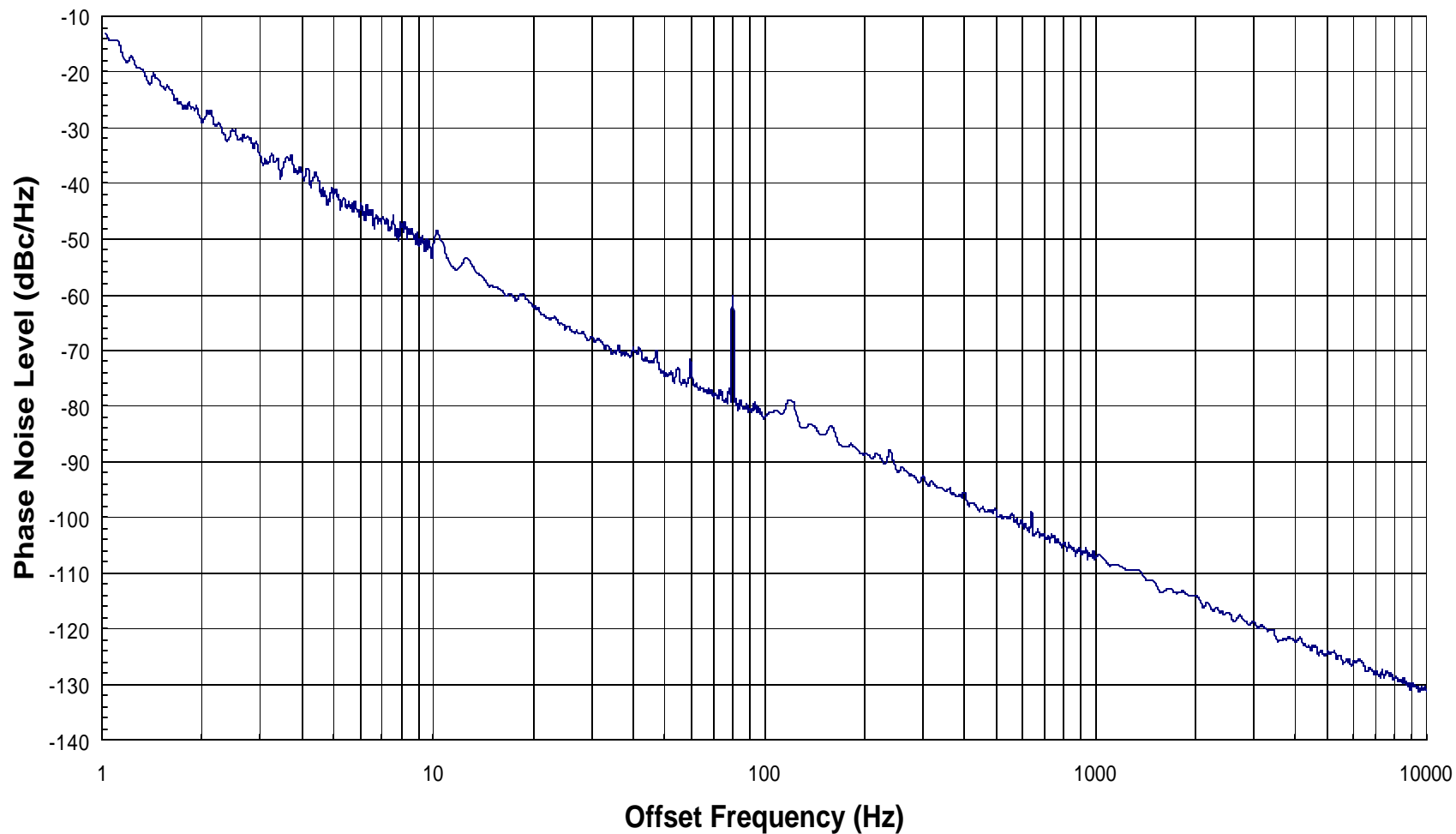
For OEO with 2km Fiber Length



APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



Phase Noise of OEO3  
(PN-FR-06, fc:6.12GHz, 08/17/00)



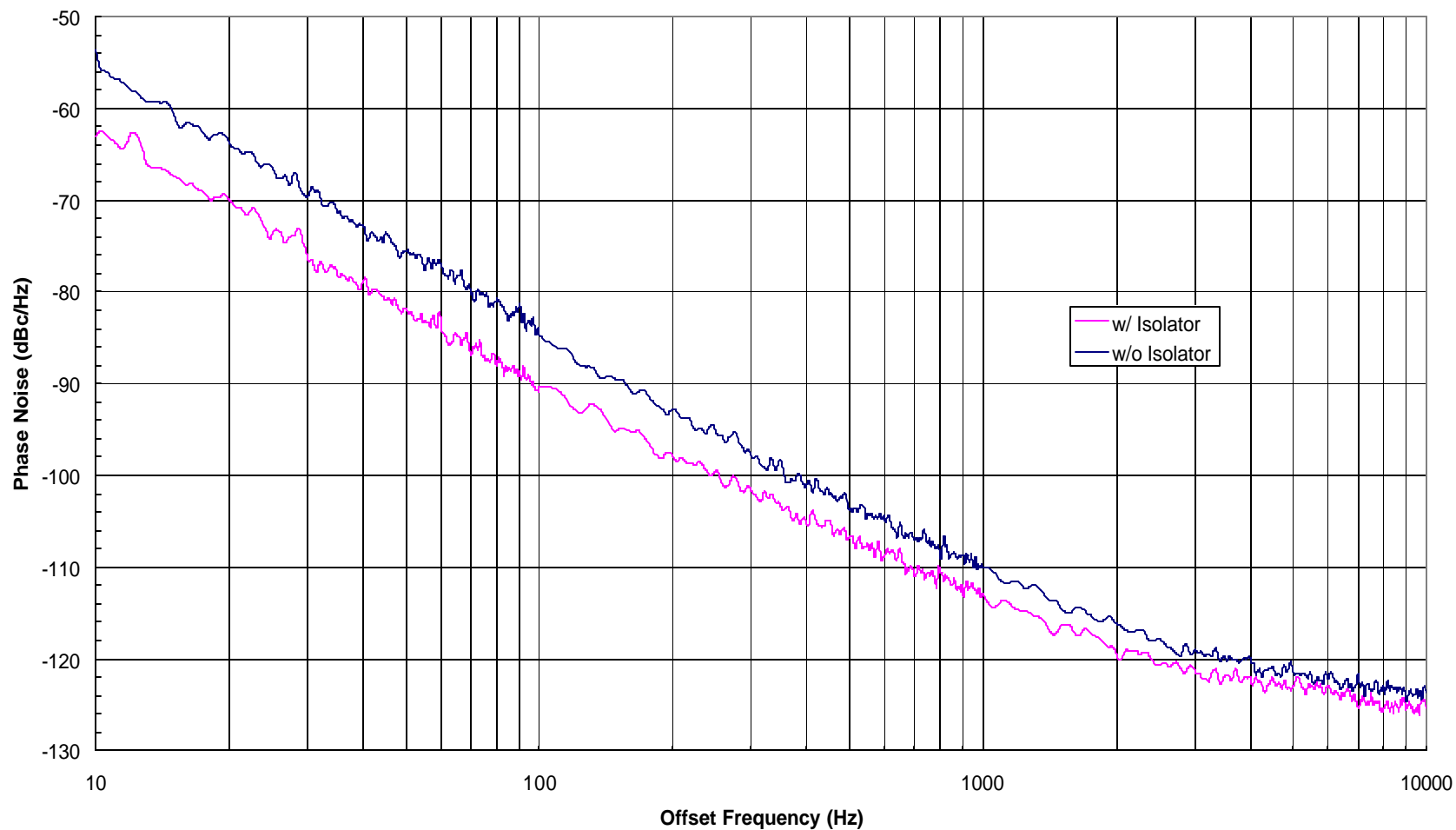
LM / AOSP 8/02

SHH5128/071902

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



Open Loop Phase Noise vs. Optical Isolator (Measured by Maser)  
(PN005, fc:100MHz, L:12km, 04/29/02)



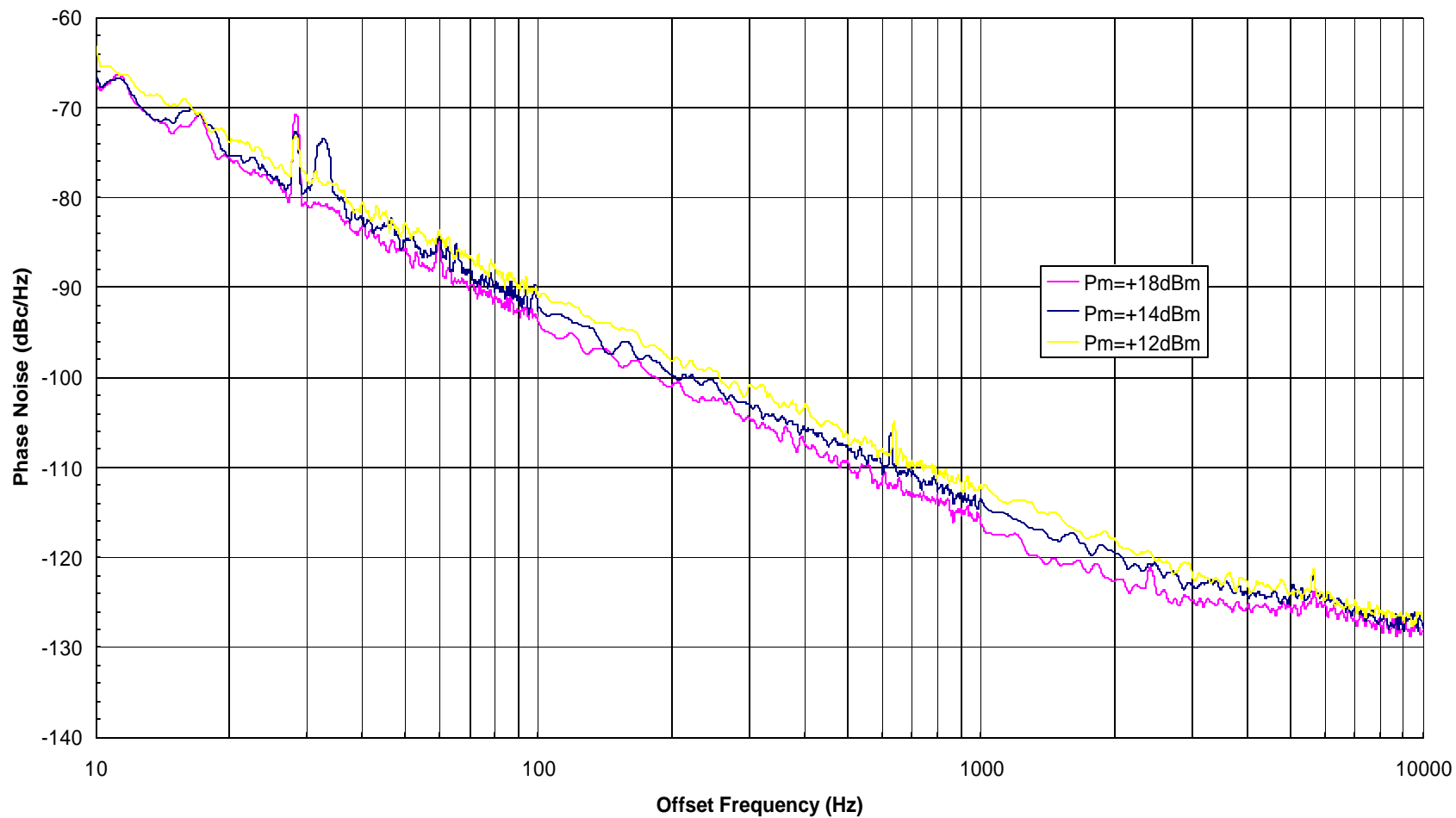
LM / AOSP 8/02

SHH5113/052002

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



Open Loop Phase Noise vs. Modulation Power (Measured by Maser)  
(PN005,  $f_c$ :100MHz,  $P_m$ :+18, +14, and +12dBm, L:4km, 05/16/02)



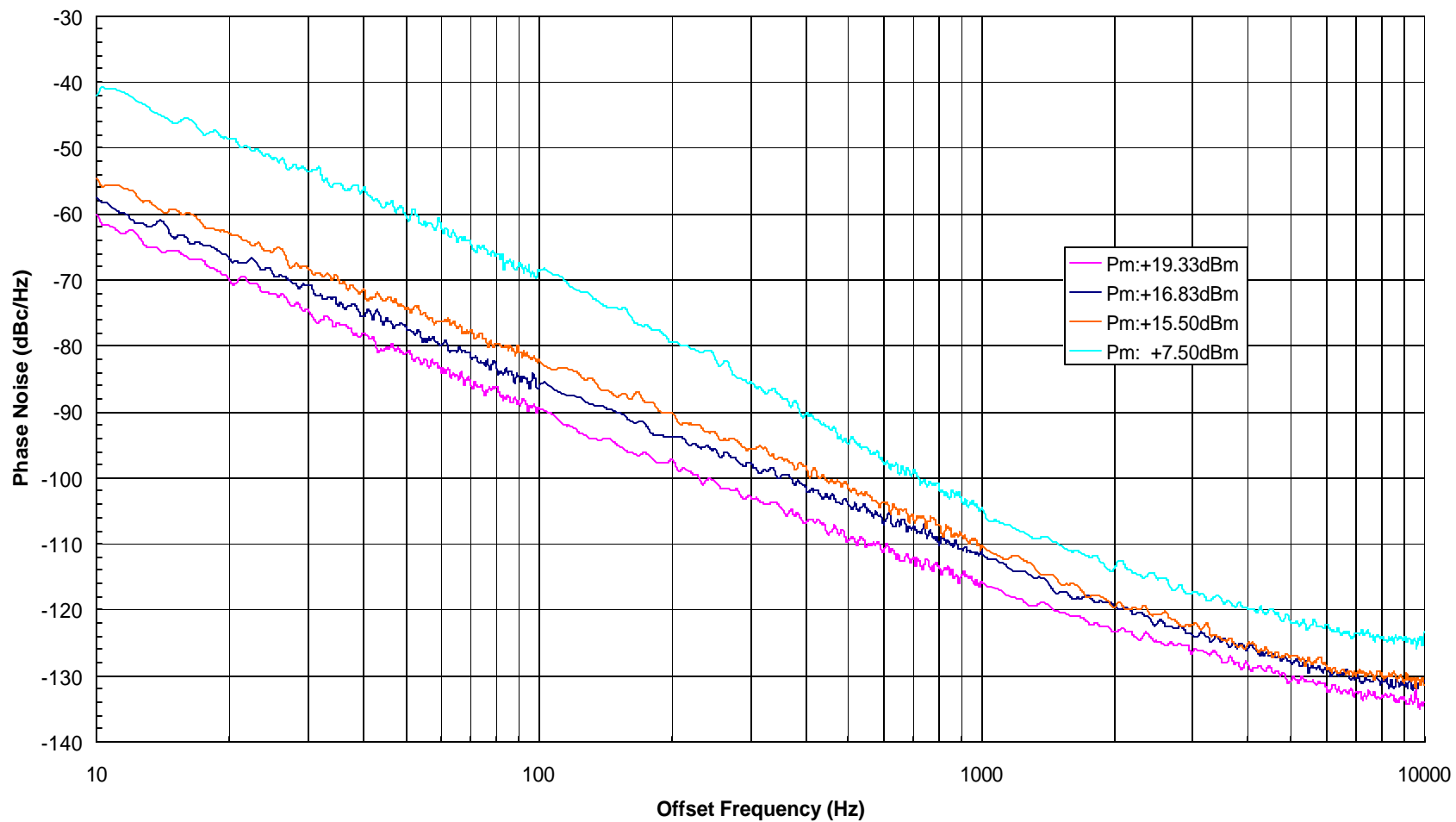
LM / AOSP 8/02

SHH5112/052002

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



OEO with Directly Modulated Laser  
(PN001, fc:90MHz, Pm:+7.5, +15.5, +16.83, and +19.33dBm, Lo:4km, 06/19/02)



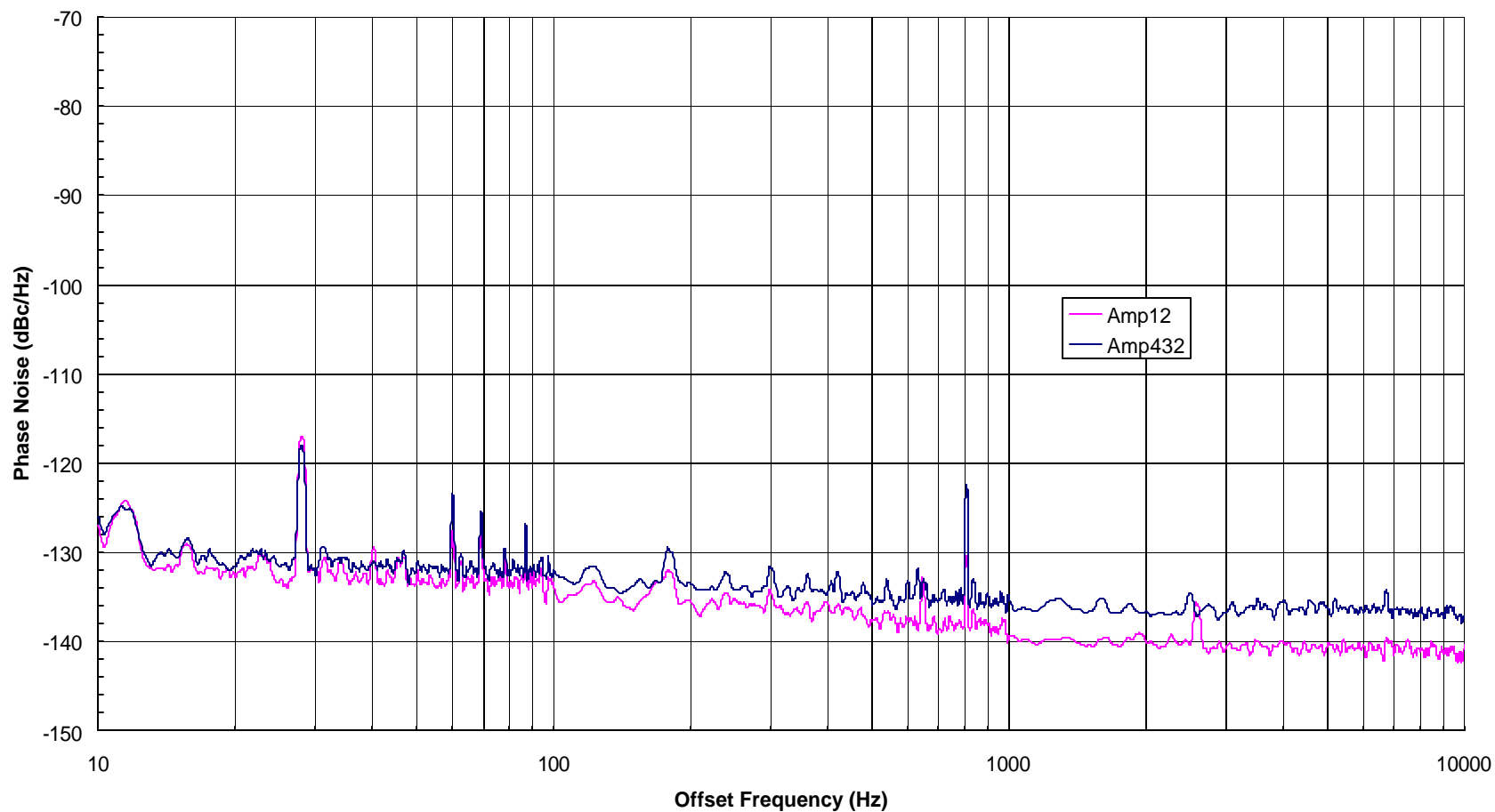
LM / AOSP 8/02

SHH5117/061902

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



Amplifier Phase Noise vs. Noise Figure  
(PN002, fc:100MHz, NF12=2.4dB, NF432=7.5dB, 05/14/02)



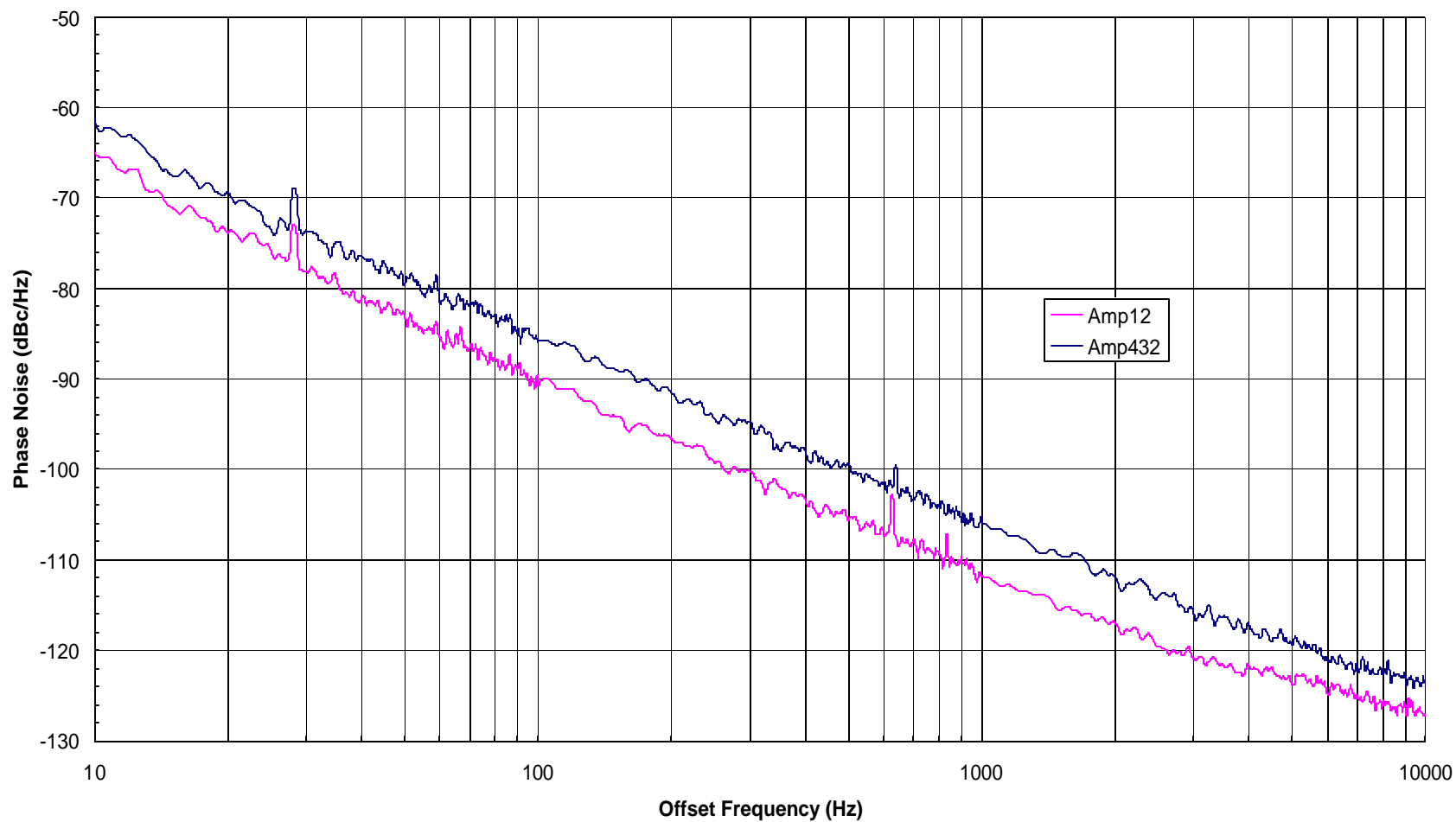
LM / AOSP 8/02

SHH5114/052102

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



Open Loop Phase Noise vs. Amplifier Performance  
(PN007,  $f_c$ :100MHz, NF12=2.4dB, NF432=7.5dB, 04/18/02)



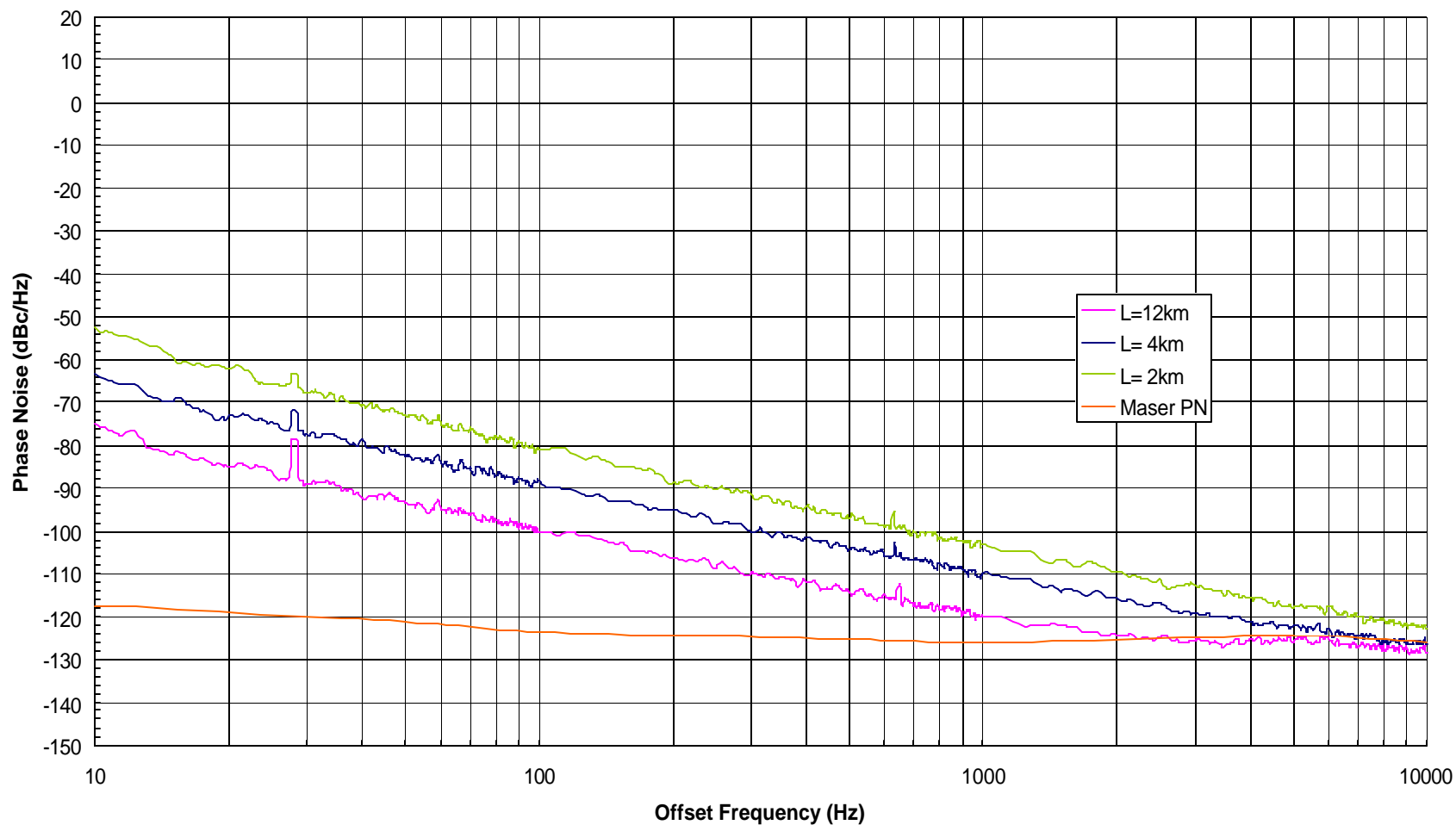
LM / AOSP 8/02

SHH5115/052102

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



Phase Noise Sensivity vs. Length of Fiber Delay Line  
(PN004, fc:100MHz, 04/18/02)



LM / AOSP 8/02

SHH5119/071602

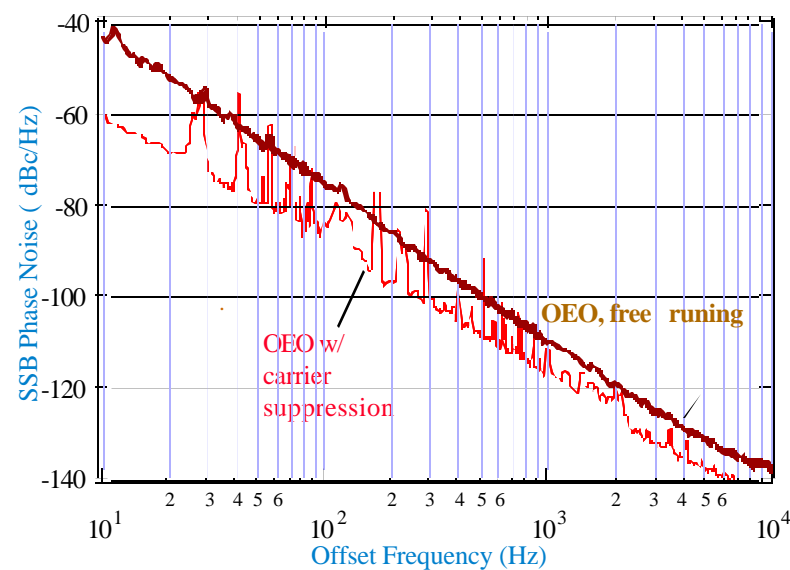
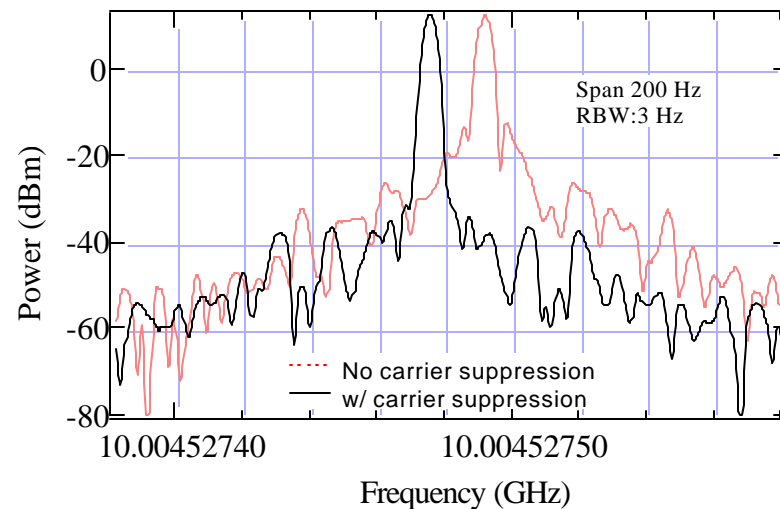
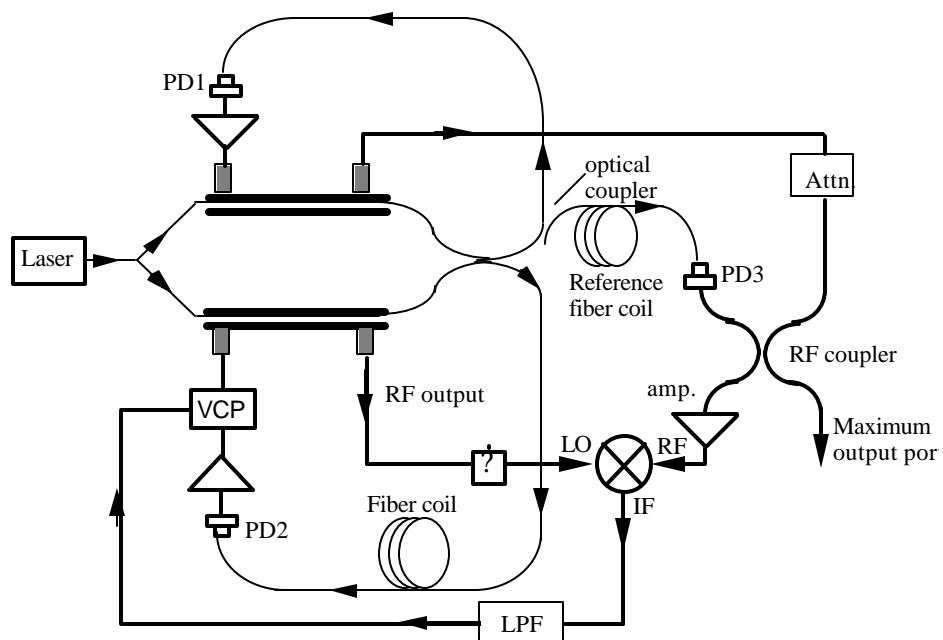
APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED



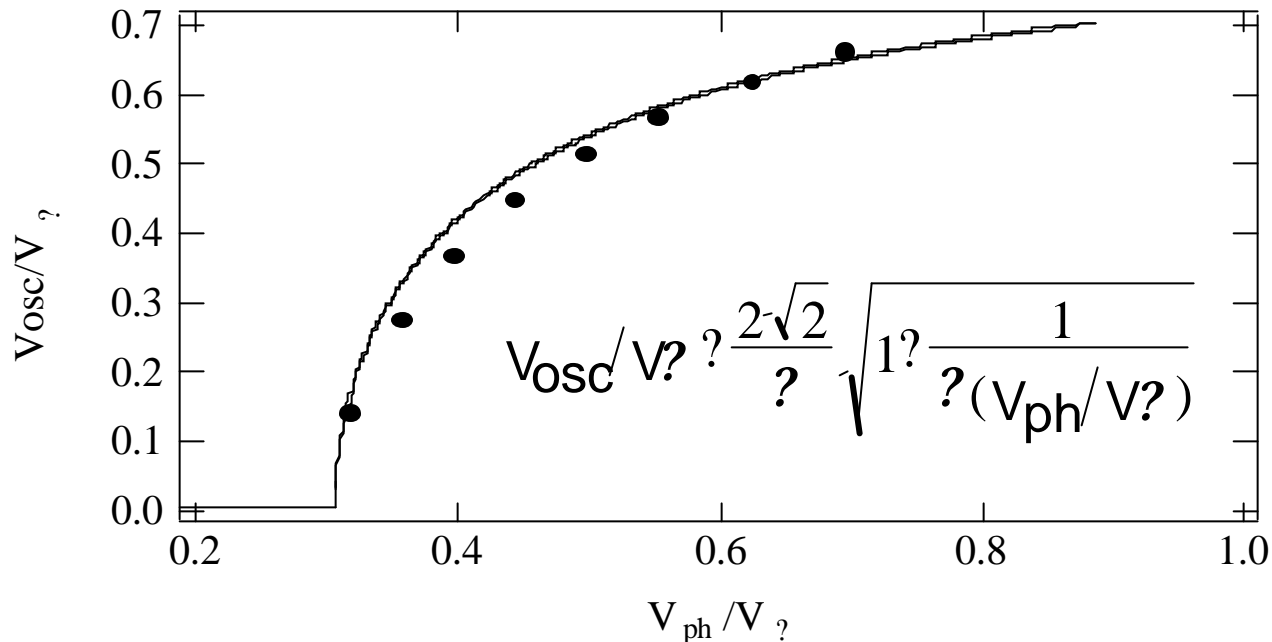
# Strategies for improving performance



- Implement configuration without the use of an amplifier to reduce close to carrier noise
  - High efficiency modulator
- Implement carrier suppression technique
  - Cancels the amplifier noise
  - Cancels residual laser RIN noise
  - Eliminates all other common noise sources



## Oscillating Amplitude vs. Photovoltage



$V_{ph} = I_{ph} * R * G$  is the photovoltage across the E/O modulator  
 $I_{ph}$ : Photocurrent.  $G$ : Amplifier voltage gain  
 $R$ : Modulator input impedance

Threshold photovoltage:  $V_{ph} = V_T / 2$

For  $I_{ph}$  of 20 mA,  $R$  of 50  $\Omega$ ,  $V_T < 3.14$  volts  $\Rightarrow$  No amplifier is required for oscillation.

LM / AOSP 8/02



## Microsphere -- a low-loss photon trap, efficient optical cavity

Whispering-gallery modes - closed circular waves under total internal reflection

(Term by J.W.S.Rayleigh, analogy to acoustic modes in the gallery of St Paul cathedral)

(MUST BE) Sustained in any axisymmetric dielectric body with  $R \gg \lambda$

low material loss (transparent material, e.g fiber grade silica)

low bending loss ( $R \gg \lambda$ )

low scattering loss (TIR always under grazing incidence  
+ molecular-size surface roughness)

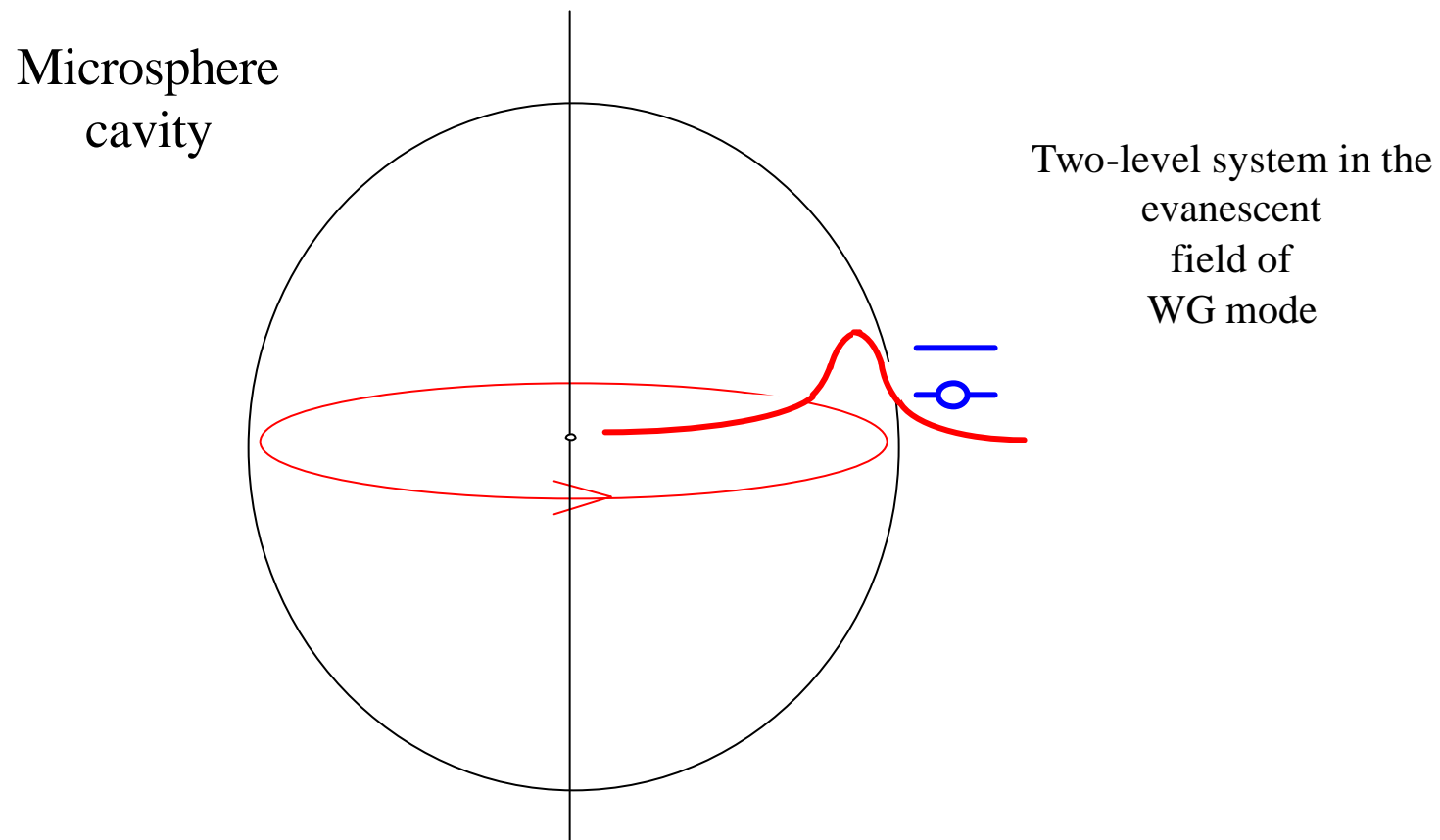
Quality-factor  $Q = \omega / \omega_{\text{RES}}$  - up to  $\sim 10^{10}$

Photon lifetime  $\tau = Q / \omega$  - up to  $\sim 3 \mu\text{s}$

(cavity ringdown time)

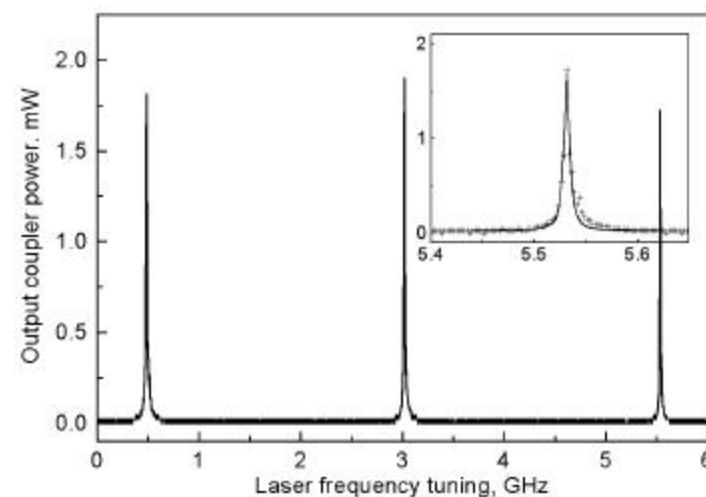
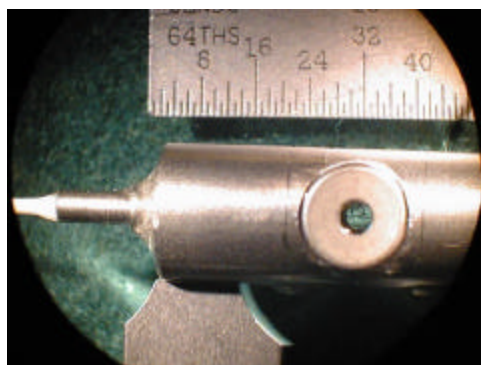
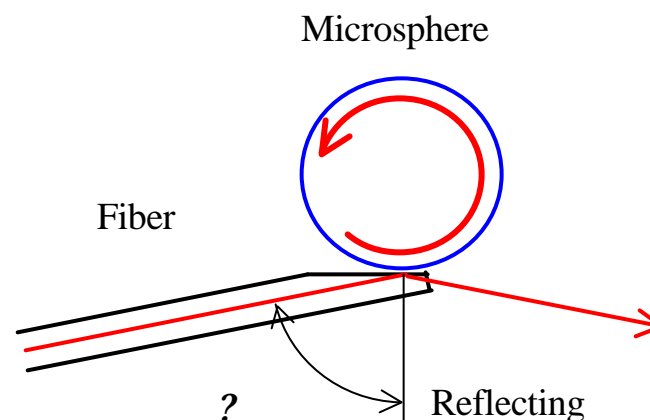
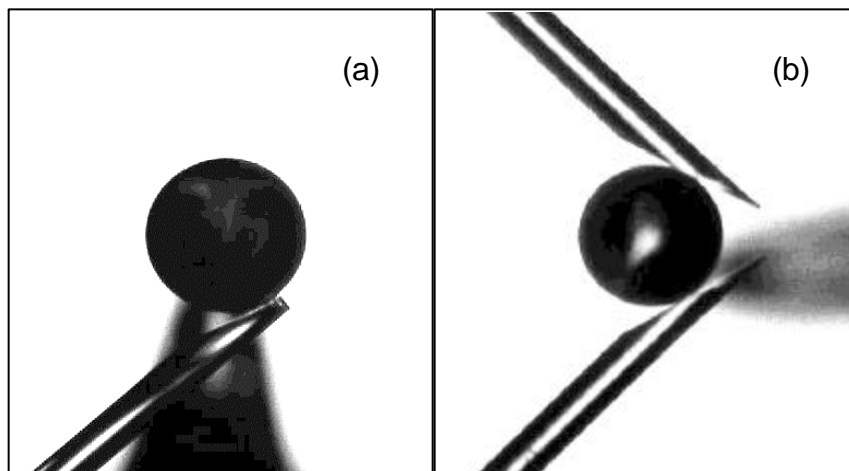
visible and near-infrared band: *Opt.Lett.* 21, p.453 (1996)

*Opt.Lett.* 23, p.247 (1998)





# Fiber-optic integration: a “pigtailed” method for microspheres

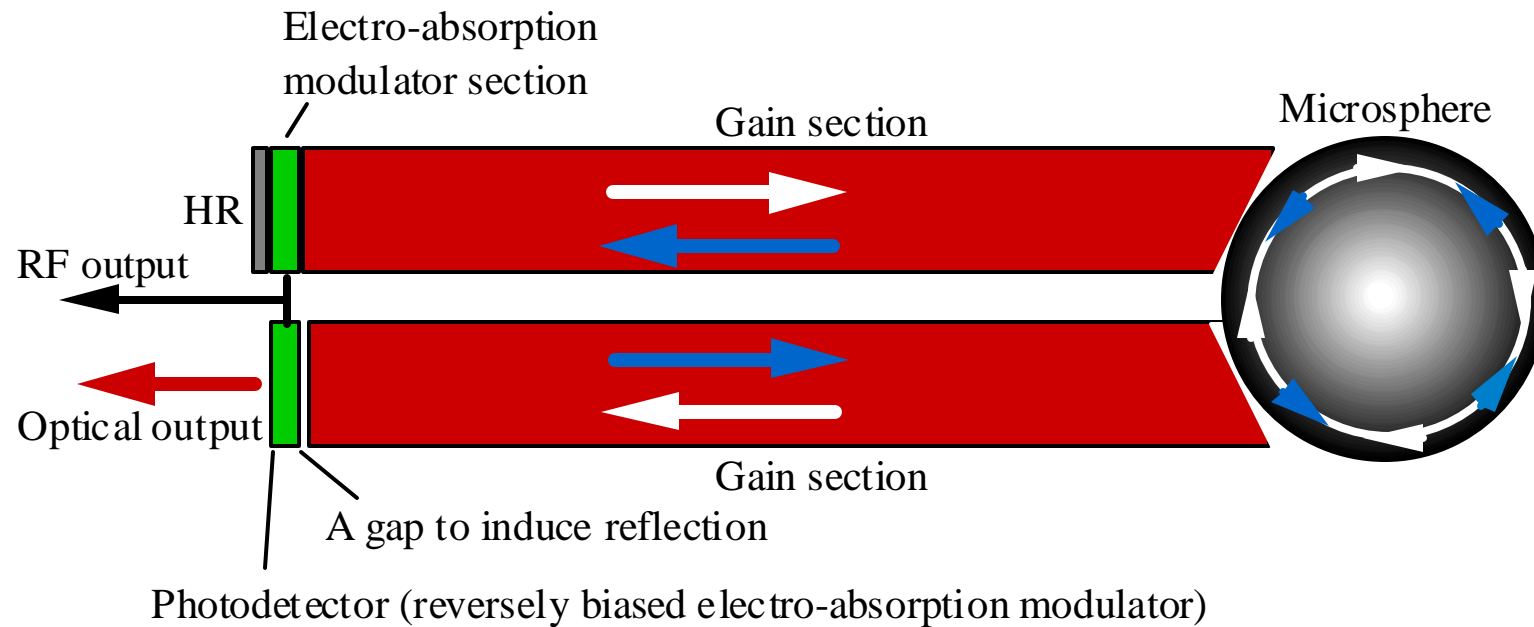


Maximum transmission at resonance ~23.5% (fiber-to-fiber loss 6.3dB);  
 $Q_{load} > 3 \times 10^7$  at 1550nm; sphere diameter 405 $\mu$ m. Unloaded  $Q_o \approx 1.2 \times 10^8$ .

LM / AOSP 8/02

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED

# Proposed mm-wave OEO-on-Chip



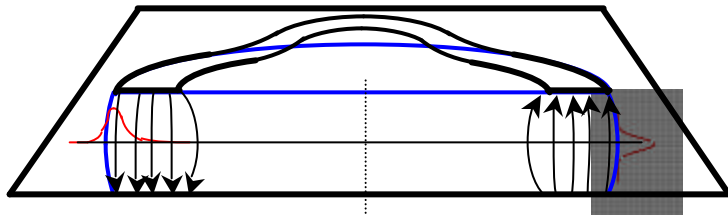
## LiNbO<sub>3</sub> Toroidal Whispering-Gallery Resonators for Ka Band Electro-Optical Modulation:



Diameter 1.45mm,  
Thickness 110micron,  
Transverse curvature  
radius 65micron,  
Optical Q ~ 10<sup>6</sup>,  
Optical FSR 33GHz



# Lithium Niobate Torus: Tunable Electro-optic Resonator / Photonic Filter

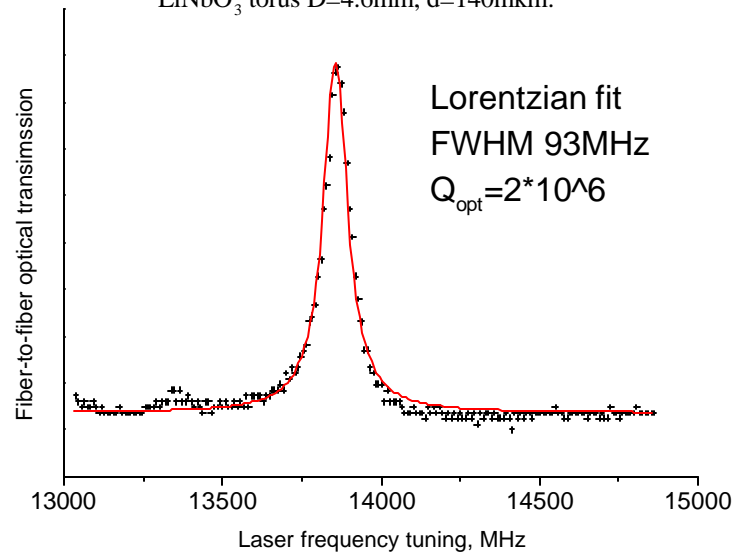


Diameter  $D=4.6\text{mm}$ , transverse diameter  $d=140\text{mkm}$ , height  $h=110\text{mkm}$ , FSR=10.0 GHz at 1550nm, optical  $Q = (2...5) \cdot 10^6$ , DC electrical tunability 5GHz

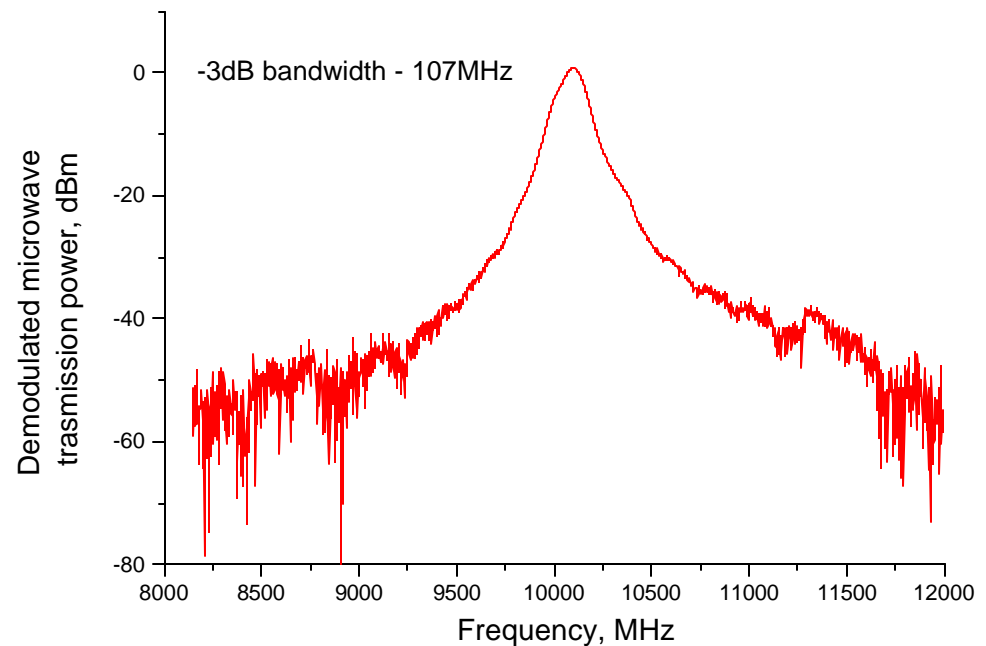
Ultra-high speed tunability -- electrooptic effect

## Optical resonance

Optical resonance, two prism configuration,  $\text{LiNbO}_3$  torus  $D=4.6\text{mm}$ ,  $d=140\text{mkm}$ .



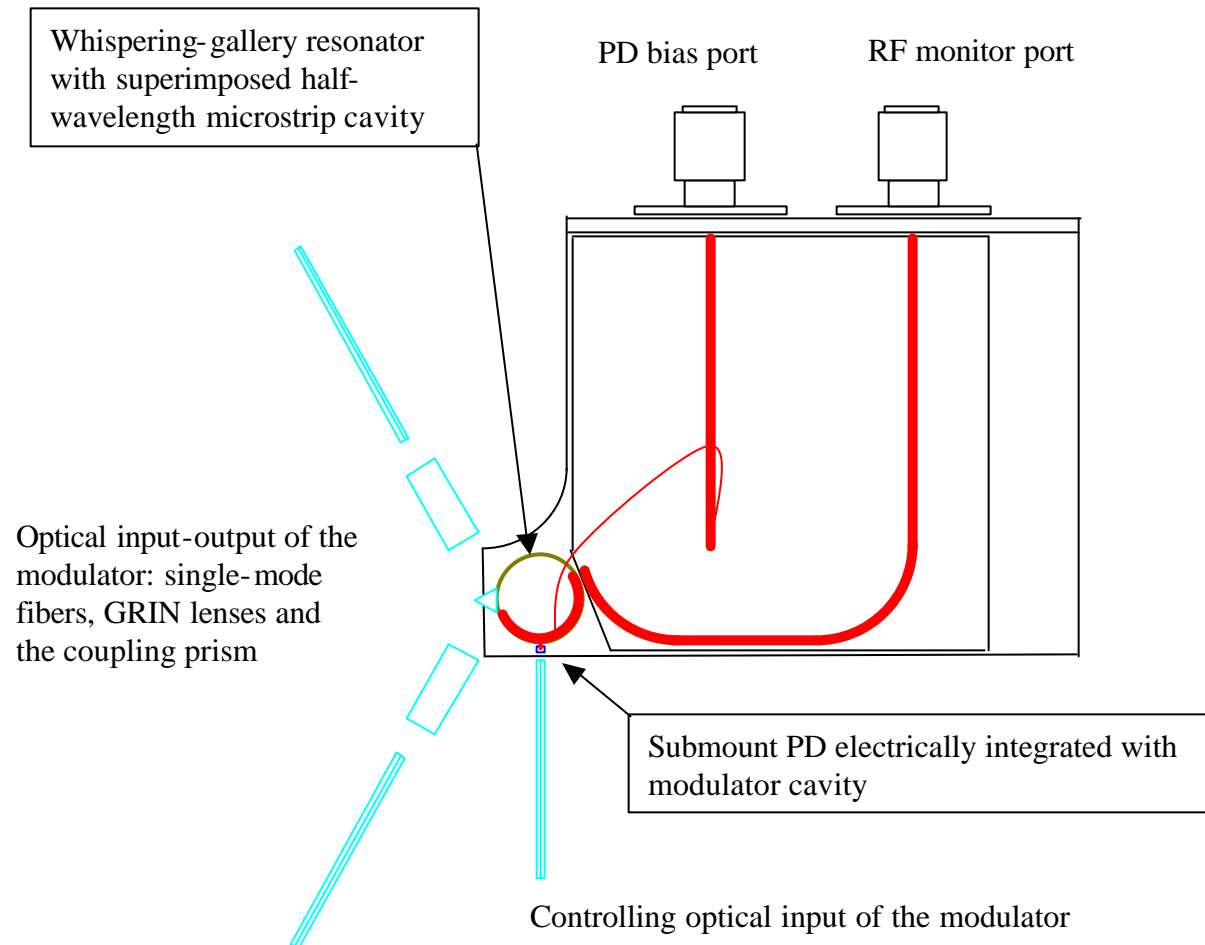
## Photonic microwave filtering via frequency selective modulation



LM / AOSP 8/02

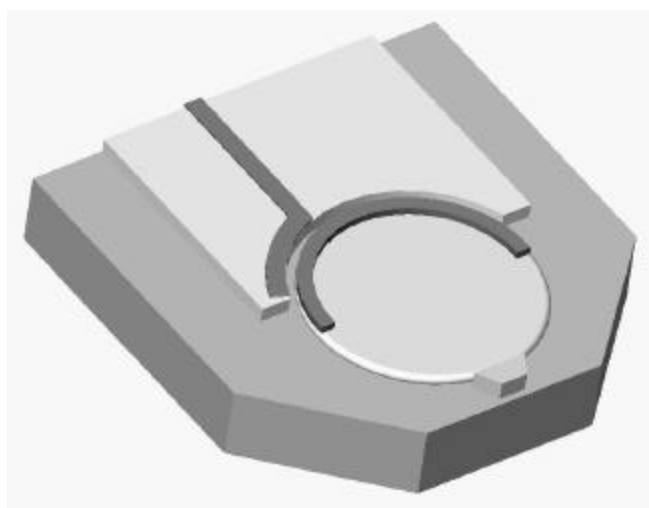
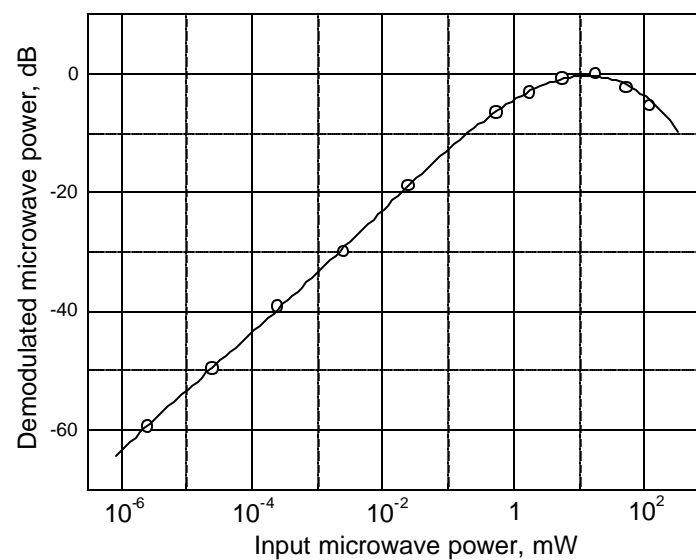
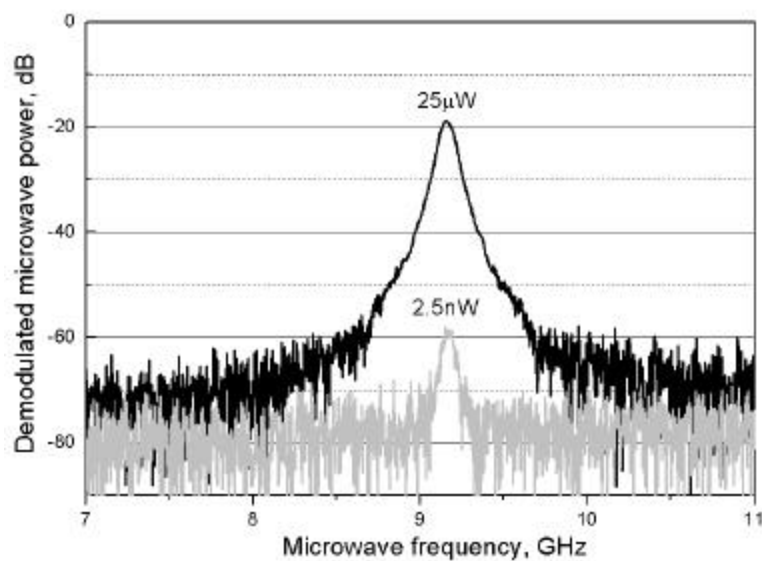
APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED

## LAYOUT OF THE PHOTODETECTOR-DRIVEN 5GHZ RESONANT ELECTROOPTIC MODULATOR





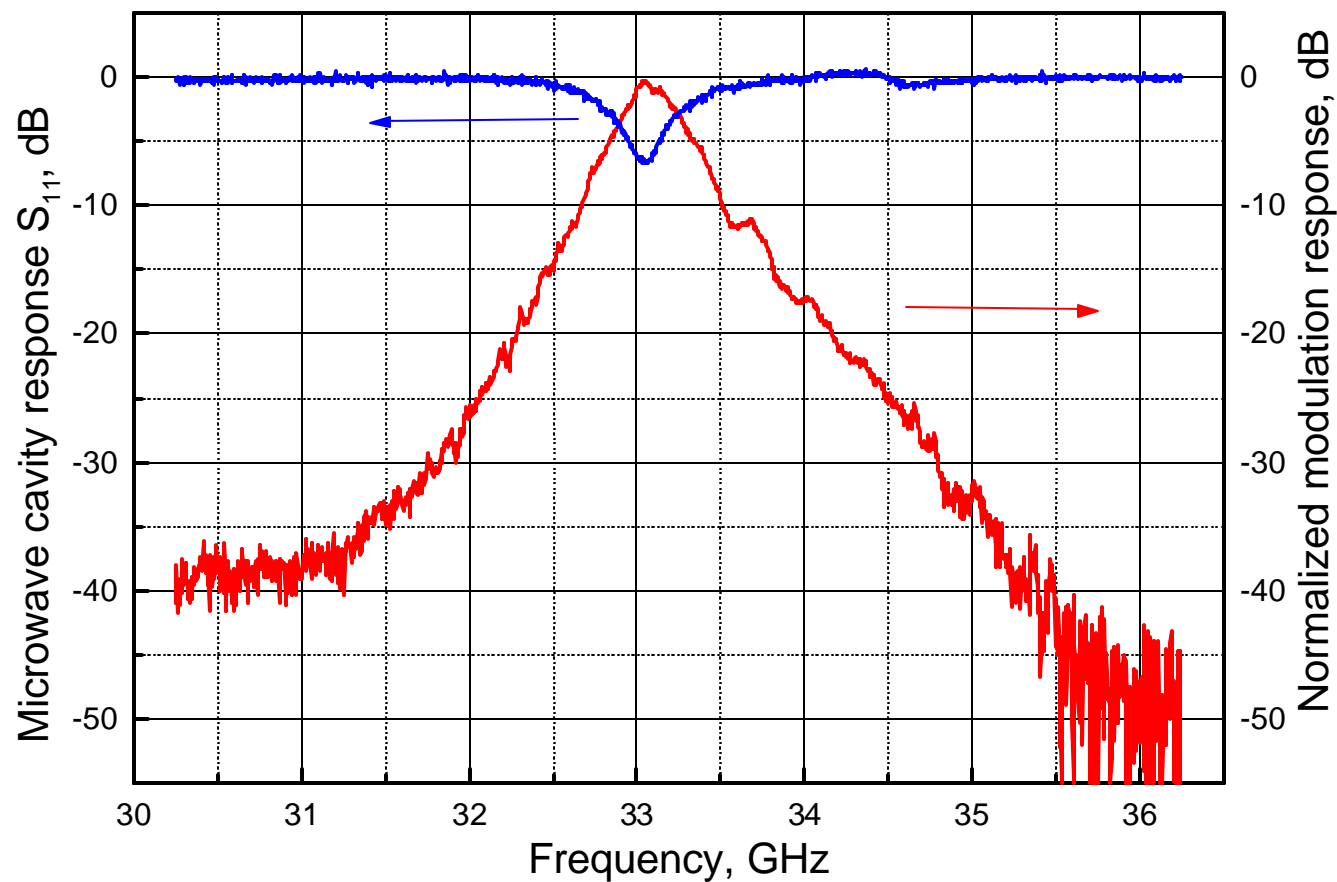
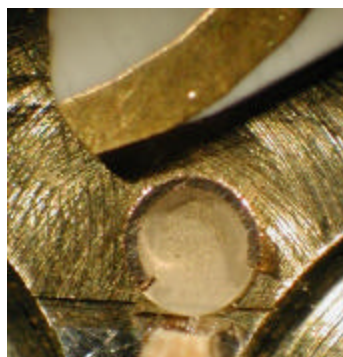
# Ultra-High Efficiency Modulator/Receiver

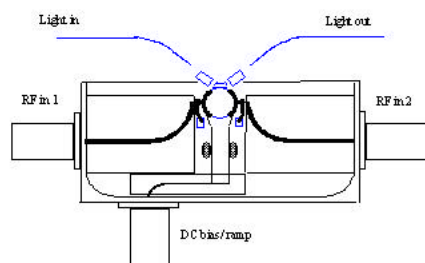


LM / AOSP 8/02

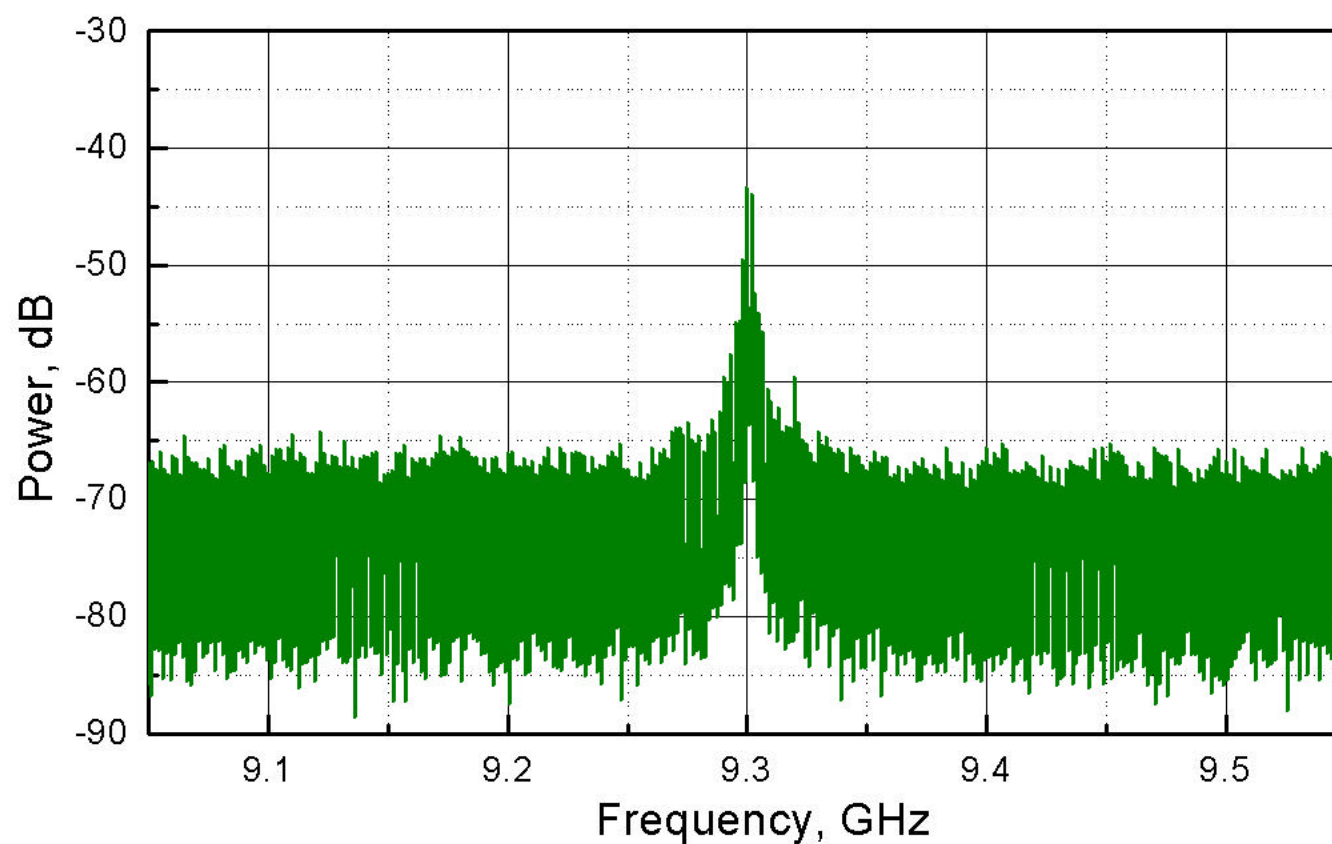
APPROVED FOR PUBLIC RELEASE – DISTRIBUTION UNLIMITED

Frequency response of the Ka band  $\text{LiNbO}_3$  whispering-gallery mode electrooptical modulator.





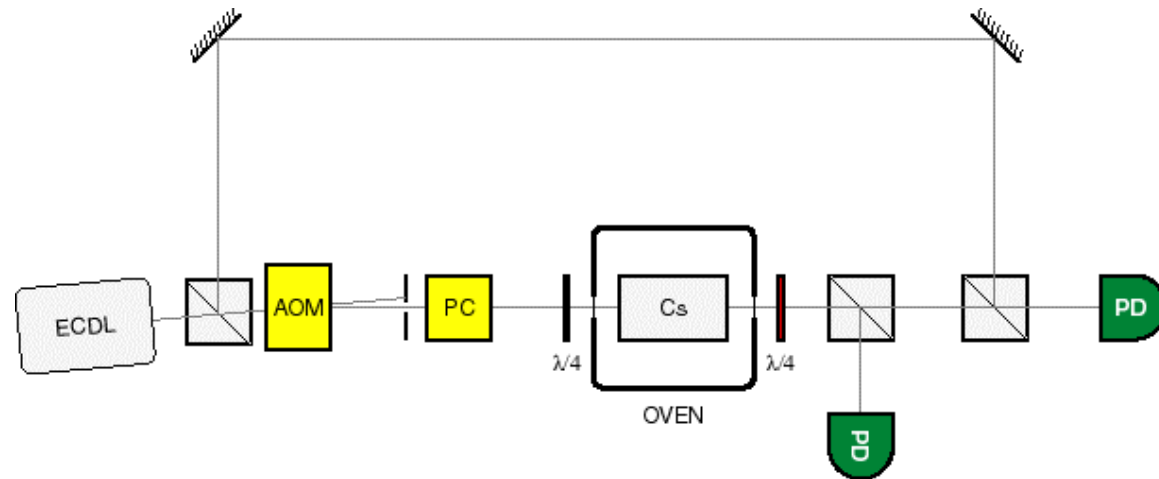
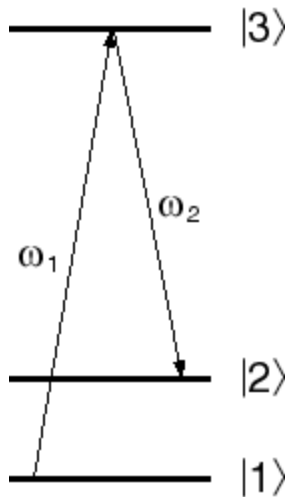
Power spectrum of the prototype OEO based on the novel WG-mode-type electrooptic modulator



Feb 9 2001



- Novel technique based on “slow light”
- Potential for precision controlled true time delay, **widely tunable**, limited only by coherence time
  - As short as 1 ns
  - Many micro-seconds of delay achievable
  - Milli-second delays possible
- Based on electromagnetically induced transparency
  - A quantum interference effect
  - Achievable with room temperature, as well as laser cooled samples of atoms



Probe laser at  $\omega_1$ , coupling laser at  $\omega_2$



# Current Status and Future Plans



- Analysis of the noise of the OEO has been completed
- Design of the slow light experiment has been completed

## **Plans for phase 1**

- Demonstrate carrier suppression with 30 dB improvement
- Demonstrate OEO without amplifier
- Demonstrate Slow light